DETERMINING THE ENVIRONMENTAL IMPACT OF DISPOSAL, RECYCLING AND REMANUFACTURING STRATEGIES

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DETERMINING THE ENVIRONMENTAL IMPACT OF REMANUFACTURING END-OF-LIFE STRATEGIES COMPARED TO RECYCLING AND DISPOSAL STRATEGIES

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NOMENCLATURE

LIST OF ABBREVIATIONS

Disposal scenario	DS
Remanufacturing scenario	RMS
Recycling scenario	RCS
Greenhouse gas	GHG
Global warming potential	GWP
Ozone depletion potential	ODP
Carbone Dioxide	CO2
Methane	CH4
Nitrous oxide	N2O
Perfluro compound	PFC
Sulfure dioxide	SO2
Percent of the total weight	wt %
Basic oxygen furnace	BOF
Electrical arc furnace	EAF

UNITS

Energy consumption	kWh/metric ton metal MJ metric ton metal BTU/short ton
Mass	kg
Liquid waste	L/metric tons metal
Solid waste	Metric tons/ton metal

CONSTANTS

GWP	
CO2	1
CH4	21
N2O	310
CF4	6500
C2F4	9200
Fuels density	
Diesel	0.833 kg/L
Heavy oil	0.9 kg/L
Fuels heat capacity	
Coal	6680 kWh/ton or 6.6 kWh/kg
Natural gas	10.55 kWh/m3
Diesel oil	10.8 kWh/L or 13 kWh/kg
Heavy oil	10.7 kWh/L or 11.9 kWh/kg

SUMMARY

In the past few decades, globalization has led to a world economy with unbounded consumption. In addition to the consequential impoverishment of natural resources, this large consumption produces copious amounts of waste and requires high energy use. Proper end-of-life strategies can help to reduce the global impact of these inefficiencies.

The objective of this thesis is to demonstrate, through life-cycles analyses of an automotive transfer case and a gear, the positive environmental impact of remanufacturing strategies compared to recycling and disposal end-of-life strategies.

In this study, the energy consumption, the air emissions and the wastes resulting from the entire supply chain's engineering processes will be quantitatively evaluated through calculations and also industrial or governmental data. In disposal end-of-life strategies, the analysis will begin with the ore mining phase, will go through material refining and processing; and eventually end with the final parts machining. In recycling scenarios and remanufacturing scenarios, the analysis will begin with the used material collection, will go through material's reprocessing or refurbishing and will finally end with the new or renewed parts machining.

This study will show the significant impact of high energy consumption processes such as electrolysis of aluminum and metal melting. It will also show how shipping and collection phases can dramatically change or annihilate the advantage of sustainable reuse scenarios depending on the sorting strategies adopted in the supply chain.

To conclude, the goal of this research is to demonstrate how remanufacturing strategies can reduce the energy consumption, air emissions and waste. This thesis will

also show how inappropriate supply chain management can negate the impact of these savings.

CHAPTER 1

INTRODUCTION AND MOTIVATION: THE ROLE OF REMANUFACTURING END-OF-LIFE STRATEGIES IN MODERN SOCIETIES

1.1 Motivations

In the past few decades, globalization has led to a world economy with unbounded consumption. The resulting high amount of waste is kept in landfills or burnt in incinerators and is responsible of soil and air pollution. Consequently, regulation has been enacted to reduce the health and environmental impacts of hazardous emissions, such as heavy metals, greenhouse gases or criteria pollutants. In addition to confirm the real danger of pollution on environment and health, these laws put a financial pressure on society and industry to change the current situation. Reuse strategies might be a positive issue of this pressure.

Reuse strategies such as recycling and remanufacturing utilize used products as primary material. Thus, in addition to reduce the amount of waste, they avoid the impoverishment of natural resources. Recycling strategies have been widely used and showed their limits in terms of positive environmental impacts. In fact, some processes such as melting processes used in recycling strategies are very pollutant and energy consuming. Remanufacturing strategies are different from recycling strategies in that the function of the reused product is conserved. Thus, no significant supplementary energy results from the production of a new part (Figure 1.1).

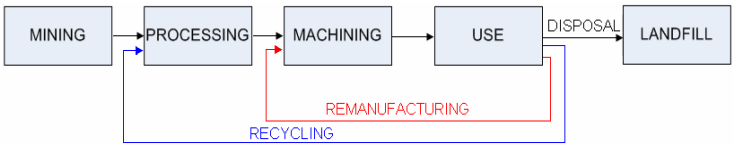


Figure 1-1 End-of-life strategies

1.2 Status and opportunities in the current industry

1.2.1 Today's industry

The last few decades and even if some material such as paper still have controversial effects on the environment, recycling strategies have been recognized to be less energy and water consuming (EPA 2006). In addition to have proved their positive environmental impact compared to disposal strategies, recycling companies have been expending successfully in the US and all around the globe. In the seventies, there were 8000 recycling facilities employing 79,000 people. Today, there are 56,000 facilities employing 1.1 Millions persons (Seldman 2002). Part of this success is justified by the cheap cost of used material compared to the high price of new products. Remanufacturing strategies are based on the same concept of reusing used and cheap material and transform it in a product with a higher value. Nevertheless, unlike recycling, remanufacturing strategies conserve the function of the part. This important difference results in less energy and natural resources consumption. In addition to these savings, remanufacturing does not require as much equipment as recycling, thus remanufacturing companies require lower investment and grow faster than recycling companies. This phenomenon already appears with the expansion of remanufacturing companies. In fact, a study of 800 companies, illustrated Figure 1.2, demonstrated that 80 % of the US remanufacturing companies employ less than 30 persons (Hauser and Lund 2003).

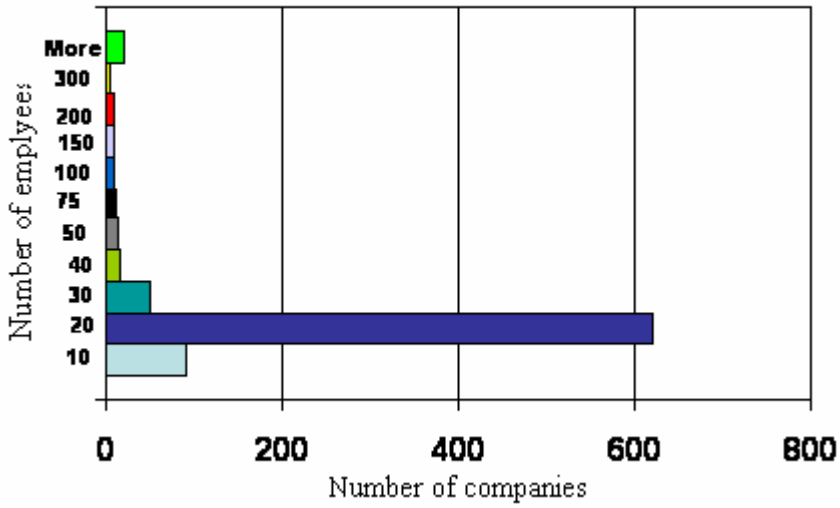


Figure 1-2 Sizes of remanufacturing companies in function of the number of workers
Source: (Lund & Hauser 2003)

This distribution shows that remanufacturing companies hardly develop in size. However, the 73,000 remanufacturing companies in the US prove the large interest of entrepreneurs into this business. Therefore, small remanufacturing companies have a high potential that needs to be exploited (Giuntini 2004). In fact, numerous US companies already developed remanufacturing strategies and have been successful. Keystone (Yoswick 2004) (Maier & Company 2007), FujiXerox (Austrialian government 2000), Kodak, IBM are examples of companies that successfully integrated remanufacturing in their design and their production. For instance, FujiXerox developed 228 new remanufacturing programs in the last decade. Thanks to these remanufacturing strategies, the savings on product sale were estimated at $25 millions for 2000.

Nevertheless, it is important to notice that all these successes were possible because of the large effort and investment in collection infrastructure. In fact, in 1990, as

Kodak started the single use camera, the company decided to reimburse the photofinishers to return the used cameras. This strategy resulted in a 63% return rate in the US and drove them to success with over 50 Million single-use camera annually sold (Fleischmann, 2001). Remanufacturing companies have still to put a lot of effort to make this strategy valuable and perennial. This will be possible with the high participation of the companies them self but also from the consumer from whom they depend.

1.2.2 The solution is to change customers, industries and governments mentalities

With 73,000 firms and $53 Billion annual sale (Hauser and Lund 2003), remanufacturing is an attractive domain that offers great profit opportunities. Nevertheless, as demonstrated below, the used material supplying requests not only a valuable organization but also the cooperation of the consumers. The collection uncertainty should be erased by strong convictions that remanufacturing strategies could help not only increasing companies' profits but also to save energy and reduce pollution. Governmental help could be necessary as in municipal recycling waste collection. This will be possible if the positive environmental impact of remanufacturing strategies is proved and that the specific purpose of the current thesis' work. The problem posed by the current work is now justified and is going to be developed and clarified in the Section 1.3 Entitled "The Problem".

1.2.3 Governments responsibilities

The US governments made a serious commitment during 2004 G8 submit, by recognizing and encouraging the importance of sustainable development and specially recognized the benefit of the "3 R" Reduce, Reuse and Recycle. "We commit to

launching the Reduce, Reuse and Recycle Initiative to encourage more efficient use of resources and materials." (The white house President Georges W. Bush 2004). These conclusions result from high efforts in the development of sustainable technologies such as Remanufacturing. It is the priority of this thesis to give reuse strategies the attention they need and disserve.

1.3 The problem

Succinctly stated, the problem consists in determining the positive environmental impact of remanufacturing strategies compared to recycling or disposal strategies. This section 1.3 will expose how to determine the environmental impact of the three strategies.

1.3.1 Definition of the environmental impacts parameters

The primary goal of this study is to determine the environmental advantage of remanufacturing strategies compared to disposal and recycling. In order to attain this goal, three parameters have been chosen. For each strategy, energy consumption, air emissions and liquid/solid waste will be evaluated and compared thanks to Life cycle assessment analyses. These three parameters are defined as follow:

1.3.1.1 Energy consumption

The energy consumption corresponds to the energy input of each phase, represented as an entering arrow in Figure 5. The types of energy used in each process are diverse. For instance, electricity is for machining processes while fossil fuels are used for transportation and gas is used for heating processes. All these energies will be taken in consideration.

1.3.1.2 Air emissions

The air emissions are even more diverse than energies. Nevertheless, for this study they have been gathered in two main groups: the *Greenhouse gases* and the *Criteria pollutants.* The first one has been chosen for its direct recognized impact on global warming and the other for its direct impact on human health.

1.3.1.3 Liquid and solid waste

The liquid waste that will get the highest attention is the water waste. In fact, this natural resource is a main concern nowadays because of its significant role in the ecosystem. The solid waste will be more diverse. Depending on the part produced, the solid waste will be mainly composed by any solid natural resource used during processing. For instance, for a steel ingot machined into a steel gear, the solid waste will be mostly made by the weight difference between the ingot and the final gear part.

All these parameters will be deeper detailed in the assumption section and in the specification section. These evaluations will make the final objective of define a minimum emission and energy consumption through a combination of disposal, recycling and remanufacturing strategies possible.

1.3.2 Application spectrum, assumptions

Determining the limits of a research is essential to guarantee a targeted and efficient work. In the analysis of LCA, determining the boundaries is also essential for the validity of the results. This section helps to understand the limits and the domain of study of the current research.

1.3.2.1 Geographical boundary

All products studied in this work are supposed to be produced in the US. Thus, all the estimations will be valid exclusively for US and will have to be carefully used for a foreign application. In fact, given the different techniques, regulations, natural resources and progress between countries, a global evaluation of emissions and energy consumption would be difficult and not accurate.

1.3.2.2 Industrial application

This research will not define new non pollutant or more energetically effective machines. In fact, industry privileges the use of cost effective machines. It will rather help to define a good combination and a good compromise between the existing strategies and existing processes. The sources of information will be mainly industrial applications and governmental regulation. The calculations will also be validated as often as possible by industrial and governmental data.

1.3.2.3 Life cycle boundary

Even if a large variety of liquid and solid waste resulting from machining and production processes is recycled in the current industry, this study will not take in consideration this possibility. In fact, for instance, green sand used in metal casting is often recycled into constructions sands, new casting molds etc… Nevertheless, this recycling results in supplementary processes such as cleaning or transportation implying additional pollutions, cost and industrial management. In addition to that, all these reuse activities depend on each company and add uncertainty to the research. This is why wastes and other outputs will be estimated as they go out of the studied system. For

instance, considering cleaning process consuming 100 L water and of which 90 % is recycled water, the consumption of water of this system will be evaluated at 100 L and not 10 L as it is the case by taking in consideration the actual reused water.

1.3.2.4 Engineering activity boundary

To conclude, designs improving remanufacturability or recyclability are out of the boundary of the study. For instance, as detailed in the Literature Review, many academic and industrial companies worked on design strategies to make products remanufacturable. This is not the purpose of the study, there will be no concern related to this domain.

1.3.3 Case study

1.3.3.1 Aluminum transfer case housing

The study will use an aluminum transfer case housing (Figure 1.2) to demonstrate differences in end-of-life strategies. A transfer case receives the power from the transmission and transfers it to the front and the rear axle. This power distribution is nowadays mostly performed by transmission belt. For a better comprehension of the studied part, Figure 3 gives a simplified schema of a whole truck transfer case. A steal gear will also be studied.

Figure 1-3 Aluminum transfer case

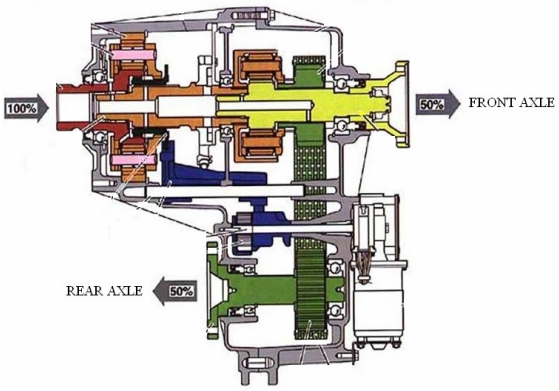


Figure 1-4 Transfer case (Wolfgang's ML 2005)

1.3.3.2 Steel gear

A steel gear will be studied to verify the observations made in the previous aluminum study. This second example will also enlarge the application spectrum of the study to ferrous materials that have different properties than non-ferrous materials such as aluminum. For instance a main difference that will be studied here is the good moldability of aluminum that results in a small quantity of material removed during the machining phase. On the contrary, still has a low moldability that results in a large amount of material removed during manufacturing. The differences between air emissions, energy impacts and waste resulting from the two materials processing will be interesting data to verify the conclusions about end-of-life strategies environmental impact.

Figure 1-5 Steel gear (Island hobbies 2007)

1.3.3.3 Case studies selection justification

Aluminum and steel were chosen because of their well established manufacture and recycling procedures. In fact, the first metal recycling has been operated in 1776 and the first recycling center was established in New York City in 1897. These dates applicable on US industry, give an idea of the minimum age of the metal recycling science. This suggests that metal recycling is a well controlled process from a mechanical point of view. Transfer case housings and steel gears are two mechanical automotive parts, widely used in the industry, that are made of these particular materials. The 100% purity of aluminum in the case of the housing and 100% of steel in the case of the gear, without any alloy is not realistic. In fact, many additives are generally used for corrosion, mechanical resistance, also manufacturability and other criteria. Nevertheless, the supposition of material's absolute purity is close to reality and first of all adapted to the problem and the need of the current study.

1.4 Analysis methodology of the three strategies

1.4.1 Disposal, remanufacturing and recycling strategies definitions

Disposal, recycling and remanufacturing definitions might be ambiguous. These following definitions complete Figure 1 and help to avoid any confusion.

- Disposal: Disposal describes the cycle beginning from the extraction of the natural resource to the disposals such as landfills or incinerators. In the current study, in order to avoid any confusion, the Disposal scenario will be named ***DS***.

- Recycling: Recycling defines the act of processing used or abandoned for use materials for use in creating new products (wordreference.com 2007). Recycling involves altering the physical form of an object or material and making a new object from the altered material (Don Van Dyke 2007). In this study, Recycling scenarios will be names ***RCS***.

- Remanufacturing: Remanufacturing is the process of restoring used products to like-new condition. (Lund 1984). Here, the Remanufacturing scenarios will be named ***RMS***.

In order to evaluate and compare the different scenarios, a methodology has been developed and is detailed in the following section.

1.4.2 Strategies environmental impacts comparison method

1.4.2.1 Case studies selection justification

The scenarios are organized in phases. These divisions detailed figure 1.6 are common to each strategy. They specify the transformation of the material during its life cycle. For instance, for all scenarios, the first phase “supplying raw material” determines how the cycle begins. In the same way, the second phase “material purification” describes how the material is transformed from a raw material into a manufacturable material.

Phase 1
Raw material supplying
Determines how the raw material is supplyed to the processing plant.
Phase 2
Material purifying
Describes the transformation of the raw material into usable material
Phase 3
Transformation of material's function
Physical, geometrical or chemical transformation
Phase 4
Final/salable function processing
Salable part is totally proceessed

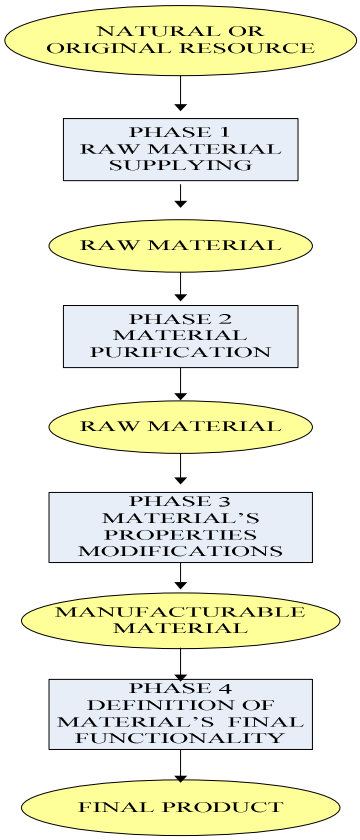


Figure 1-6 Division of the strategies into 4 common phases

The Following Figures 1.7.a and 1.7.b are two very important views of the scenarios organization respectively for aluminum and steel. These Figures detail the processes used in the four phases given in the previous Figure 1.5. These flow diagrams will be used as reference in the study. For a better comprehension, each process is detailed in the following "Parallelisms and differences between scenarios" section.

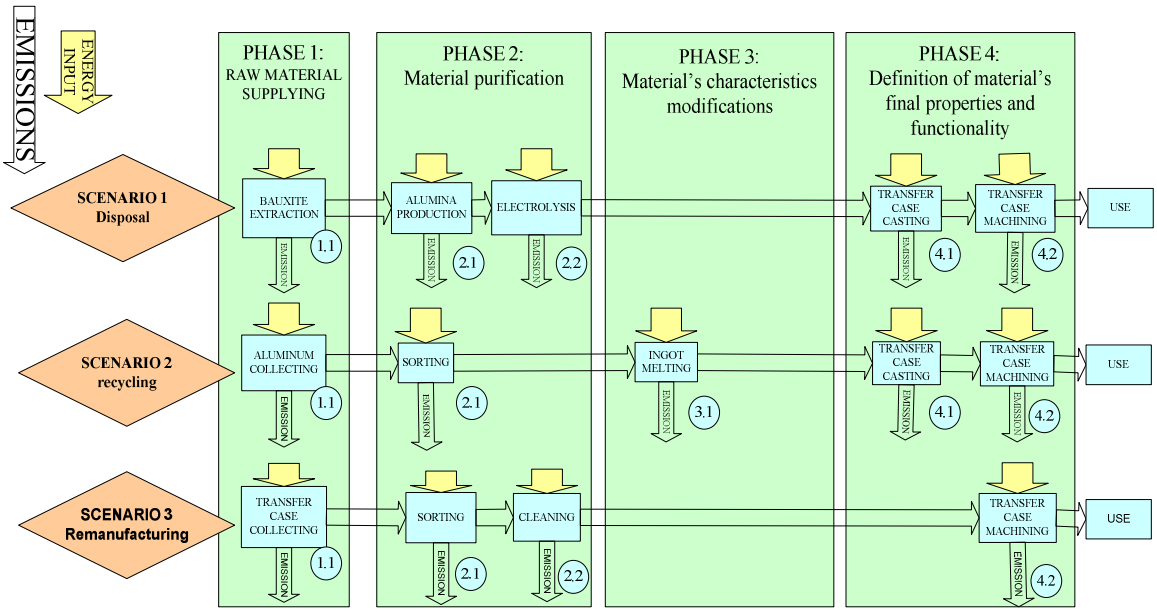


Figure 1-7.a Three Scenarios organization applied to Aluminum

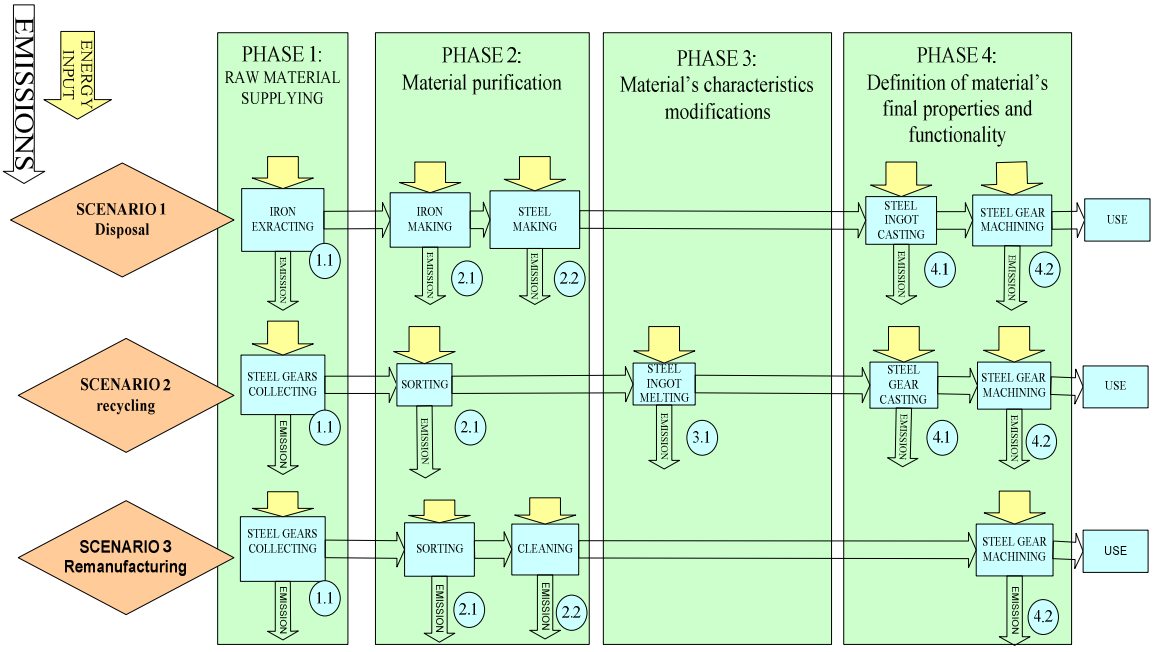


Figure 1-7.b three scenarios organization applied to Steel

Figure 1-7 Three scenarios organization

1.4.2.2 Parallelism and differences between scenarios

The four phases determined Figure 1.7 are common to all scenarios. These phases are composed by sub-phases or processes that depend on scenarios and case studies. The processes necessary to produce recycle or remanufacture aluminum transfer cases and steel gears are detailed below.

Aluminum

Aluminum DS: As determined Figure 1.7.a, aluminum disposal scenario begins with the extraction of the ore called Bauxite, it corresponds to Phase I. After extraction, this raw material is supplied to aluminum manufacturing plants where Bauxite is transformed into Alumina (Al_2O_3) (Sub-Phase 2.1, Phase II). Alumina is then transformed into molten aluminum through Electrolysis (Sub-Phase 2.2, Phase II). As mentioned before, aluminum is assumed to be cast right after the Electrolysis sub-phase (Sub-Phase 4.1 Phase IV). Finally the functional surfaces of the part are machined (Sub-Phase 4.2, Phase IV).

Aluminum RCS: Recycling aluminum scenario begins with any aluminum parts collection. For instance, in the case of municipal waste collection, the aluminum might be shipped to recycling facilities with other recyclable material such as paper, plastic or glass and shipped. This is why; the second phase of recycling begins with the sorting process (Sub-Phase 2.1, Phase 2). Once aluminum has been insulated, it is sent to a melting process where the primary function of the used part is annealed (Sub phase 3.1, Phase III). It is important to notice that the melting process also plays the role of material's purification. In fact, thanks to melting; the impurities of the used aluminum are easily captured and taken away from the pure aluminum mixture. Nevertheless, given the

fact that the main function of melting is to change the function of the part, and for clarity reasons, this sub-phase will be part of Phase III. The casting is performed and gives the molten material a shape and a function close to the salable part (Phase 4.1, Phase IV). The functional surfaces are machined during the last phase, after what, the part is salable (Sub-Phase 4.2, Phase IV).

Aluminum RMS: As in recycling scenarios, remanufacturing phases begin with the collection of used parts. Nevertheless, these used parts are only aluminum transfer cases housing or system containing such parts (Sub-Phase 1.1, Phase I). The After this supplying phase, the parts are sorted in function of their reusability and potentially separated from the system they were provided with. For instance, in the case of the aluminum transfer case housing, the whole transmission might have been transported to the remanufacturing plant. After sorting, the parts are cleaned (Sub-phase 2.1, Phase I). Once cleaned, the functional parts that might have been damaged during the previous life are machined and made functional again. This important phase of manufacturing strategies and all other sub phases introduced below, will be detailed in the life-cycle analysis section.

Steel

Steel DS: As in the aluminum scenarios, disposal strategies begin with the extraction of ore (iron ore). It is then followed by the shipping of raw material to the manufacturing plant. Iron ore is then transformed into steel material. The liquid steel is then case and machined.

Steel RCS: Recycling strategies begin with used material collection. The collected waste is shipped to the recycling plant where waste is sorted. During sorting steel

material is extracted from the rest of the waste. The material used for steel recycling is steel. The parts collected do not have necessary the same function as the final gear. In fact, collected parts can be steel can, steel civil construction parts, etc…The sorted steel is then molten, spent to case and machined. The two last steps of casting and machining are the same as in disposal scenarios.

Steel RMS: Steel remanufacturing processes begin as recycling processes by the collecting of used parts. The used parts are shipped to the remanufacturing plant where they are sorted. The parts sorted here that will be remanufactured are steel gears. In fact as mentioned before, remanufacturing scenarios do not change the function of the part. After being sorted, the part is cleaned. Machining is then necessary to restore the functionality of the part.

1.4.3 Analysis quantitative and qualitative specifications

1.4.3.1 Units specifications

A meticulous analysis of life-cycles assessments is necessary to define all outputs of each process. The final part (ready to be used) produced by all scenarios is the *salable aluminum*. Energy use will be estimated in *kWh/ton salable aluminum*. One transfer case housing weights 4.1 kg. Thus, the unit of one ton salable aluminum is equivalent to 244 salable parts. Air emissions are given in *g/ton salable aluminum*. While comparing processes energy consumption is trivial; comparing their air emission is more difficult. In fact, there exist several types of gases emitted that can not be compared to each other directly. This is why, it is important to determine the gases that are going to be focused and how they will be compared to each other.

1.4.3.2 Qualitative specifications

Greenhouse gas

Academicians and governments have recognized the effects of certain gases and have classified them depending on their impact. Gases that have an influence on global warming are considered as greenhouse gases. The emissions studied here that belong to this category are CO_2, CH_4 and N_2O. In order to estimate their global impact, they will be converted into *kg* $CO_{2\ equivalent}$ */ ton salable aluminum,* thanks to international standards given Table 1.1.

Table 1-1 Emissions equivalences (EPA 2007)

Category	Formula	Name	Category potential
Greenhouse gas	CO2	Carbon dioxide	1
	CH4	Methane	21
	N2O	Nitrous oxide	310

These three gases are not the only greenhouse gases emissions. They are focused here because of their massive emissions resulting from human activity.

Criteria pollutants

Other gases called "Criteria pollutants" have an impact on environment but also on human health (EPA 2007). They are defined by EPA as "air quality indicators". Six gases belong to this category: Ozone (O_3), Nitrogen dioxide (NO_2), Sulfure dioxide (SO_2), Particulate Matter (PM), Lead (Pb) and Carbon monoxide (CO) (EPA 2007). Ozone is not directly emitted into the air but results mainly from chemical reactions between NO_x and VOC with sunlight exposition. Evaluating O_3 here is susceptible to

bring redundancy and uncertainty in the calculation given the exterior parameters such as light, temperature influencing the reactions. This is why; O_3 will not be studied here. Particulate matters (PM) are made of dust, soot, smoke and all solid particles emitted in the air. They result also from condensation and transformations of SO_2 and VOC_s in the atmosphere. For these reasons, PM_s will not be taken in consideration here. Lead emissions have a direct impact on human health. Ingested or inhaled by air, lead causes serious central nervous system damages and heart diseases. To summarize, the criteria pollutants that will be focused here are: SO_2, NO_x, Pb and CO.

VOCs and heavy metals

In addition to these two emissions categories, volatile Organic Compounds (VOC_s) and heavy metals such as mercury will be analyzed in this study (EPA 2007).

The emissions will be estimated in *g/ton salable aluminum.* The emissions that will be studied here are summarized in Table 2. There exist ways to define equivalence between gases. For instance SO_2 and NO_x participate to the acidification of the rain and consequently lakes and soils. Their effect could be evaluated in function of the acidity (amount of H^+) they might produce. Nevertheless, given the numerous impacts of criteria pollutants and other compounds such as VOC_s or heavy metals, the conversion will be left to the reader.

Table 1-2 studied emissions specification

	Chemicals formula	Name
Greenhouse gas	CO2	Carbon dioxide
	CH4	Methane
	N2O	Nitrous oxide
Criterial pollutants	SO2	Sulfure dioxide
	NOx	Nitrogen oxides
Other	Pb	Lead
		VOC

Liquid and Solid waste

To conclude, liquid waste and solid waste are going to be studied. Estimating natural resources are indispensable here to measure end-of-life strategies impact. Nevertheless, it is necessary to define the boundaries of this study. The quantity of natural resources (coal, gas, fuel…) consumed by power generation will not be specified here. In fact, evaluating this resource would be redundant with the energy consumption evaluation. The amount of waste evaluated here will be considered without any recycling or cleaning issue. In fact, post treatments are responsible of supplementary pollutions and energy consumptions and depend on companies' strategies and environmental policies. This uncertainty parameter will be excluded from the current study.

Before beginning the analysis, it is important to determine what has been done so far on the subject presented in the former sections. This step is important for two main reasons. In fact, it is capital to take advantage of the data and studies done in the past but also it is indispensable to avoid a work already done. Both are indispensable for a successful and sustainable progress.

CHAPTER 2

RESEARCH BACKGROUND

2.1 Introduction to LCA analysis standards

Life-cycle analysis (LCA) assessment is "*a method to account for the environmental impact associated with a product or service*" (SETAC work group 1997) and is the fundament of this study. Therefore, it is important to be familiar with the LCA analysis methods and their standards ISO 14040, 14041, 14042, 14043. The method described in these standards is composed by four phases:

Table 2-1 Four phases of life-cycle analysis

1	2	3	4
Goal and Scope	Inventory analysis	Impact assessment	Interpretation

The first step "Goal and Scope" consists in defining the purpose, the boundary and the units of the inputs and outputs that are going to be evaluated. The second step or "Inventory analysis" is the data collection. In this study, data result from calculation and from governmental sources. These sources have been chosen to reduce uncertainty and disputability in the results. To conclude, the two first steps are ruled scrupulously by ISO 14041. The third phase or "impact assessment" helps to evaluate the environmental consequences of the previous phase's results. ISO 14042 guides the construction of this third phase. Finally, the "interpretation" is to comment and draw conclusions about the

three previous steps. ISO 14043 articulates this last step. Significant work on LCA related to this study's domain has been done in the past. This is going to be detailed in this section and will help to define the work that remains to be performed.

2.2 Life cycle assessment literature review

2.2.1 Material production

The aluminum and steel metals studied here are produced by ancestral and standardized processes that are clearly determined and explained in numerous sources. The references used in this study were issued from governmental documents (Environment Protection Agency (EPA) 2007) (Energetics Inc. for US Department of Energy 2000) (Energetics Inc. for US Department of Energy 1997). These documents give information about primary and secondary material.

As it will be demonstrated in this study, industrial sources were also important processes information and significant sources of data (World-Aluminum 2007) (The Aluminum Association Inc 2007) (Mc Bee 2001).

2.2.2 Life-cycle assessment (LCA) analysis

The LCA study will be done with the support of several works performed on the same topic. LCAs examples (Udo de Haes 2006) will be necessary support as well as more specific studies such as End-of-Life strategies LCAs analyses (Muir 2006) (Smith & Keoleian 2004) (Facanha 2005). Different conclusions on reuse strategies environmental impacts depending on the application result from these works. This shows how reuse strategies environmental benefit depends on the application domain and therefore justifies the need of the current study. Some work also provide important data

source for aluminum and for steel end-of-life strategies LCAs (International Aluminum Institute 2000) (SteelUniversity.org 2007) (Curran 2001). Important data concerning specific manufacturing processes such as casting are also available and will be used in this study (Dalquist 2004). Detailed reusing procedures will be important guidelines for life cycle inventory and analysis. In fact, working on reliable recycling and remanufacturing supply chains is capital to guaranty accurate and liable results (Russel 1996) (Piwonka 2001). To conclude, other domains such as cleaning products LCAs were explored. Cleaning is an essential part of remanufacturing processes and might be an important agent of pollution given the solvent and large amount of water needed (Vollebregt 1998) (European Chlorinated Solvent Association (ECSA) 1996). This is why the conclusions and the data of such studies will be very helpful here.

2.2.3 Design for Reuse

Design for reuse is out of the current work's boundaries. Nevertheless, the approach made in some works is useful and should be considered as necessary references. In fact, in addition to bring interesting data and comments about the current market and the difficulties that Remanufacturing strategies might meet, they also prove the difficulty to generalize remanufacturing applications. Works in Design for Reuse determined how to discern a reusable product from a not-sustainable one. These discussions emphasize the importance of simplicity and anticipation to disassembly in the design of products (Amezquita 1996) (Behrendt 1997). Another work on design focused on design for the environment gives very interesting comparisons between materials and manufacturing processes. It also helps to identify the needs of a more environmentally conscious design and production (Gutowski 2004). In addition to that, another issue common to works on

remanufactured products design is the benefit of associating remanufactured and new components in one product (Geyer 2003) (McIntosh and Bras 1998). This observation will also be discussed in the current work, where the question of combined scenarios environmental impact is raised. An important governmental information source on waste and pollutants emissions in the US will be very helpful in this study. The data provided will significantly help to justify the necessity of reuse strategies development (Environmental Protection Agency 2005).

2.2.4 Regulations for cleaner technologies

The current work focuses on natural resources savings, pollutions emissions and waste reductions. In addition to serve the environment, this study is necessary to industries because of the increased financial stake of environmental protection. In the last decade regulations have been enhanced and taxes on pollutions have been increasing. The rules and the financial stakes help to justify the goal and the being of the current research (Environmental Protection Agency 1987-2007) (United Nations Framework convention on Climate Change 1997) (United Nations Environment Program 2000) (Environmental Protection Agency 1990-2000). Ozone depletion substances ruled by the Montreal Protocol will be helpful for the identification of allowed and currently used cleaning solvents necessary in remanufacturing scenarios. Industrial Greenhouse gases emissions have been discussed and regulated by the Kyoto Protocol. These treaties show that environmental concerns have gained an industrial and political size and therefore are serious issues to be discussed and improved. From an industrial point of view, the raise of polluting cost and taxes can justify the current work. Polluting taxes and price existing and forecasted can be found in the literature (Murphy 2001) (Sohngen 1998)

2.3 Remanufacturing literature review

The objective of this study is to determine the environmental benefit of remanufacturing strategies. This is why, knowing as much as possible about current activities and existing studies on the specific subject of remanufacturing is essential. This section is entirely dedicated to remanufacturing industry and techniques.

2.3.1 Remanufacturing history

Beginning with the insulated transformation of one steam frigate into an ironclad ship in 1861 (National Center for Remanufacturing and Resource Recovery (NCR3) 2003-2006), Remanufacturing expended to 70,000 companies in the US in 1996, attaining a large scale industry of $53 billions/year income (Lund 1996) (Lund & Hauser 2003) (Giuntini 2003)

2.3.2 Remanufacturing fundament: closing the loop

Remanufacturing strategies close the "loop on the material flows". […] "Associated with product or service delivery to consumers, these reusing strategies have been proved to be efficient and indispensable for sustainable development. Nabil Nasr developed an approach similar to the current thesis work, where he demonstrated the benefit of entirely closed consumptions system called "Resource Flow Models" (Nasr 2006). This work is one supplementary valuable justification of the work performed here.

2.3.3 Strategic phase of remanufacturing: collection

A big effort has been done on collection strategies and organization with different associations and companies. Examples show positive results on benefits and remanufacturing companies growths. These encouraging cases emphasize that organized

collection is a capital parameter in the remanufacturing strategies success. One example is the non-profitable organization "Intervol" case. In order to be able to collect medical equipment and reuse them, Invertol with the financial support of Environment Investment Program, nominated an Executive Director responsible of the material supplying responsibility. This resulted in a $240,000 savings on disposal fees for the New York State. This is one of numerous examples that prove the main role of collection in the End-of-Life strategies impacts and benefits (Environment Investment Program (EIP) 2000). This is why Chapter 5 "Transportation's energy consumption inventory analysis" is dedicated to the study of collection's impact. Other studies have been done on collection and more generally on transportation. They gave the current work guidance and precious source of data (Center of Transportation Analysis 2006) (Yoon 2005) (US Department of Transportation 2007). Energy consumptions and air emissions data depending on collection distances and reuse strategies are available thanks to case studies realized in the past years (Zheng 2004) (Facanha 2005).

2.3.4 Remachining techniques

The remachining techniques that exist and are currently used in the industry are an essential resource for this research. Companies reports and advertisements for remanufactured parts (DG Engine services 2007) (TransAxle 2007) give a good idea of the recent or standard techniques of remanufacturing. Guidelines for re-use processes are also available. In these studies, remanufacturing processes are clearly detailed and help to build correct life-cycles. In addition to show the processes necessary in a reuse chain; these guidelines also show the risks and the important step to follow in remanufacturing scenarios strategy designs (Bras 2006) . In those studies, the important parameters and

that guaranty viability to the re use strategies are clearly determined. In addition to the remachining techniques existing in the industry, other significant information resources are the machining processes. Machine retailers catalogues (the PMT group 2006) (KISTLER 2006) (MAKINO 2007) are useful source of information to determine remachining energy uses and energy consumption. In fact remachining and remachining processes use the same type of machines, with different cut parameters. In addition to catalogues, essential knowledge about machining energy consumption comes from literature (Gutowski 2004) (Dalquist 2004). The decomposition and analysis of energy consumption during machining are an important step in machining science and will be widely used in the current study in Chapter 4 "End-of-life strategies transformation processes energy consumption inventory analysis", Section 4.2. In addition to re-machining processes, another characteristic of remanufacturing strategies is the cleaning phase. This purification step will be inspired by general cleaning processes applied on other domains than remanufacturing (Environment Protection Agency (EPA) 1994) (Environment Protection Agency (EPA) 1996). Catalogues of cleaning machines (MART Corporation 2007) (UNIWASHERS 2007) (LS Industries 2006) (ASCO Carbon Dioxide LTD 2007)and solvents (Cole-Parmer 2007) (Dow Chemical Company 2007) (Euro Chlore 2007) are also an essential source to determine realistic industrial uses and applications. Thanks to the willing of companies to participate in the amelioration of solvents efficiencies and environmental impacts, energy consumption, waste and air emissions rates and are available in the literature. They are realistic and relevant sources for the current study (New York State Energy Research and Development Authority (NYSERDA) 2004).

2.4 Literature review summary

To conclude, the current work will estimate the environmental impact of three end-of life strategies, disposal, recycling and remanufacturing scenarios. To perform this analysis, two case studies, an aluminum transfer case and a steel gear will be used. As developed previously, lot of work has been done on aluminum and steel life cycle analysis. They will be widely used in this study. Governmental data such as Energy Information Administration (EIA) (Energy Information Administration 2007), Environmental Protection Agency (EPA) (Environmental Protection agency 2007), Department of Energy (DOE) (Department of Energy 2007) and Transportation Energy Data Book (Center for transportation analysis 2006) will be preferred to verify calculations results. Finally, it is important to remember that design for remanufacturing is a very important source of data but is out of the boundary of the study and therefore will not be studied in this work.

CHAPTER 3

IDENTIFYING DISPOSAL, RECYCLING AND REMANUFACTURING PROCESSES

3.1 General structure of all scenarios

This following section is dedicated to the good understanding and the detailing of the three end-of-life scenarios. Phases and sub-phases are going to be detailed with their input and output. As mentioned in the previous sections, scenarios are divided into four main phases that are raw material supplying, material purification, material's properties modifications and material's final functions and properties definition. This organization applies to the aluminum transfer case and to the steel gears, as it is going to be detailed in the following sections.

3.2 Aluminum transfer case production scenarios structure and processes

The aluminum transfer case housing weights 4.1 kg and is a cast part. It is assumed (for the clarity of the study) to be made of 100% aluminum, with a 2.7 kg/dm^3 density. The alloys generally added for corrosion and other concerns are not taken in consideration here. Figure 3.1 is a simplified schema of the transfer case studied here.

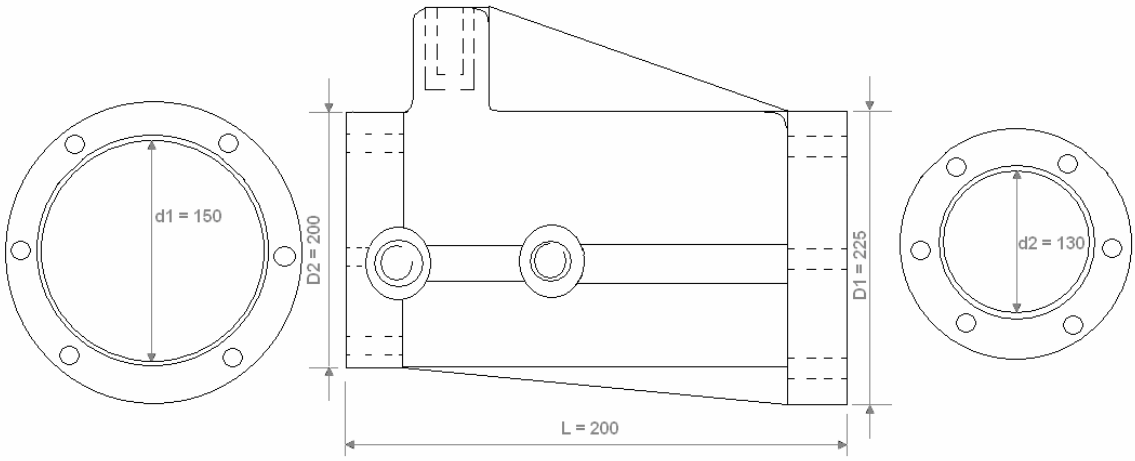


Figure 3-1 Aluminum transfer case geometrical specifications

The three scenarios that are going to be studied here are illustrated in Figure 3.2. The following section is dedicated to the descriptions of these scenarios. Figure 3.2 will be often referenced and should be kept in mind all along the thesis.

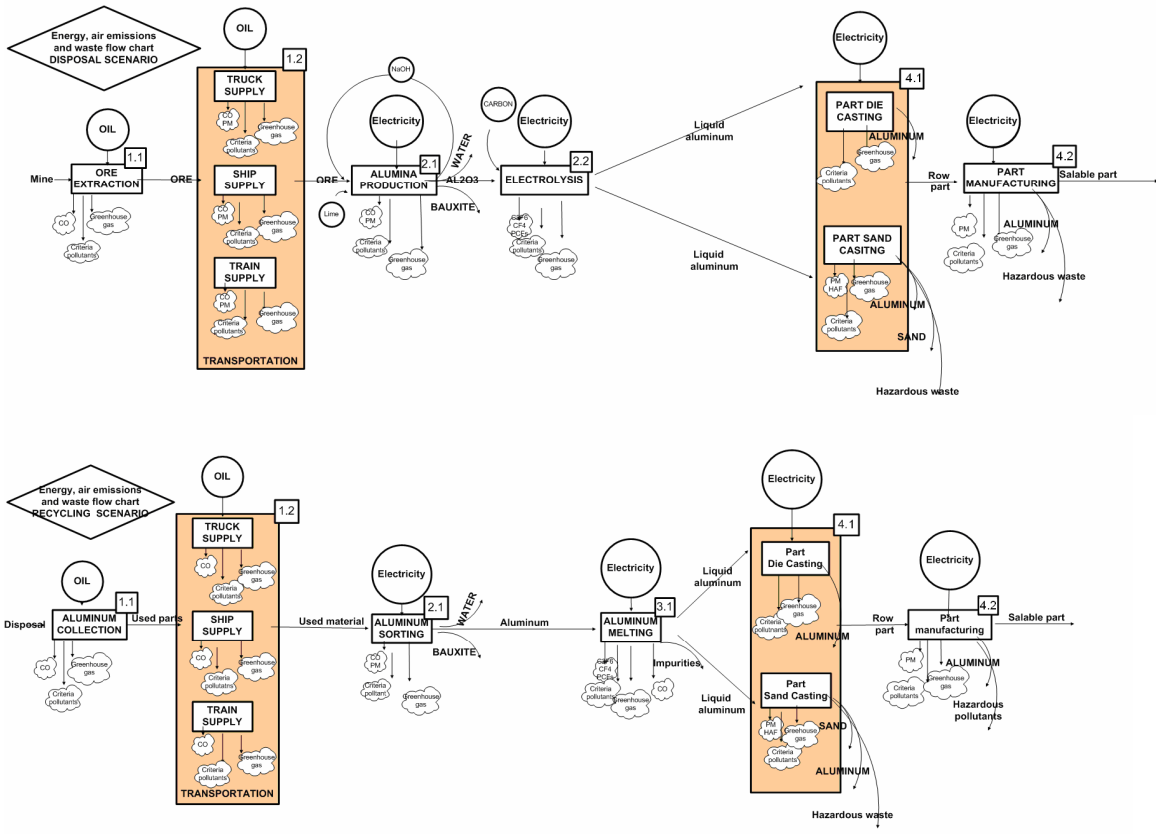


Figure 3-2 Scenarios processes for Aluminum transfer case

3.2.1 Aluminum transfer case Disposal Scenario (DS) description

As it is shown Figure 3.2, the aluminum part is realized in four phases. The first phase is the extraction of Bauxite. This ore is then transported to the production plant. The second phase follows with the transformation of bauxite ore into Alumina (Al_2O_3) through grinding, crushing and heating processes associated to caustic soda solution. Alumina is then transformed into Aluminum through Electrolysis. The third phase in disposal end-of-life scenarios is empty. In fact, aluminum coming out of the electrolysis is liquid and all processes are realized on the same site, therefore, no remolding process is necessary here. In the fourth phase, the molten aluminum resulting from electrolysis is sent to casting. In this study, two different casting processes both widely used in the industry have been studied. They are die casting (permanent mold) and sand casting (single use mold). After casting, the functional surfaces are machined. The part is then finished and ready to be sold. The selling phase is not part of the study. The final shipping part depends on customers and market. This last transportation step is out of the study's boundaries.

3.2.2 Aluminum transfer case Recycling Scenario (RCS) description

The primary material of recycled aluminum parts is used aluminum. This aluminum is present in many objects such as aluminum cans and automotive parts. As mentioned before, the recycling of aluminum domain has been largely explored by academies and companies and thus will be very briefly described here.

Used aluminum is assumed to be collected with other recyclable used parts such as glass, plastic bottles, paper etc... This waste is transported to the recycling plant where the aluminum is sorted preliminary from the rest of the used material. The melting

process realized after sorting has two functions. The first one is to get the material ready for casting and the second one is to separate the impurities from the pure aluminum. The pure aluminum is then sent to casting and follows the same procedure as disposal strategies. In fact, the part is then machined to acquire its complete functionality.

3.2.3 Aluminum transfer case remanufacturing scenario description

The remanufacturing cycle begins as the recycling cycle. Nevertheless, one major difference has to be underlined. The used parts that are going to be used are transfer cases housing. As in recycling strategies, these housing might be collected with other parts such as whole transmission for instance. Remanufactured parts were used parts whose functions have been restored and even improved compared to the original state.

Remanufacturing cycles begin with the collection of used transfer case housings that are brought to remanufacturing facilities. There, the housings are separated from the other collected parts and are controlled. Depending the way parts have been used (age, constraints, shocks…), cracks, surface defaults might appear that make the part not remanufacturable without supplementary cost or processes. After being controlled, parts are cleaned. The machining is the last step. This last refurbishment process is dedicated to give functionality back to the parts. Depending on the type and the state of the part, cleaning and machining might be unnecessary. Electronic components are examples that usually do not need to be cleaned or machined. Nevertheless, given the fact that the worse case of remanufacturing is analyzed in this study, these two steps will be entirely considered.

3.3 Steel gear production scenarios structure and processes

The second case study is a steel gear that weights 6.25 kg. This part is assumed to be made of 100% steel with a density of 7.8 kg/dm^3 and machined in one steel cylinder. Figure 3.3 shows the gear that is going to be studied here and its geometric specifications.

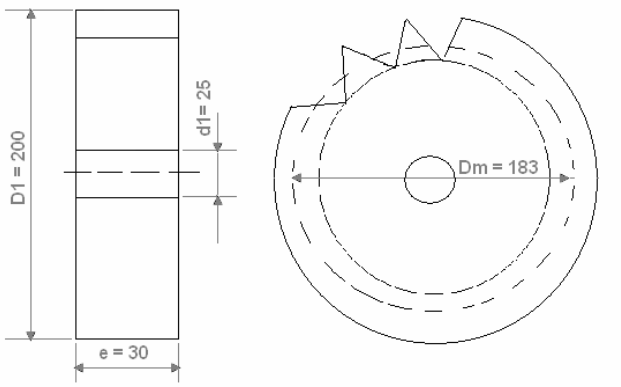


Figure 3-3 Steel gear geometric specifications

The three steel gear scenarios are illustrated Figure 3.3. This Figure will be referenced in the following section and all along the study and therefore should be carefully observed and kept in mind.

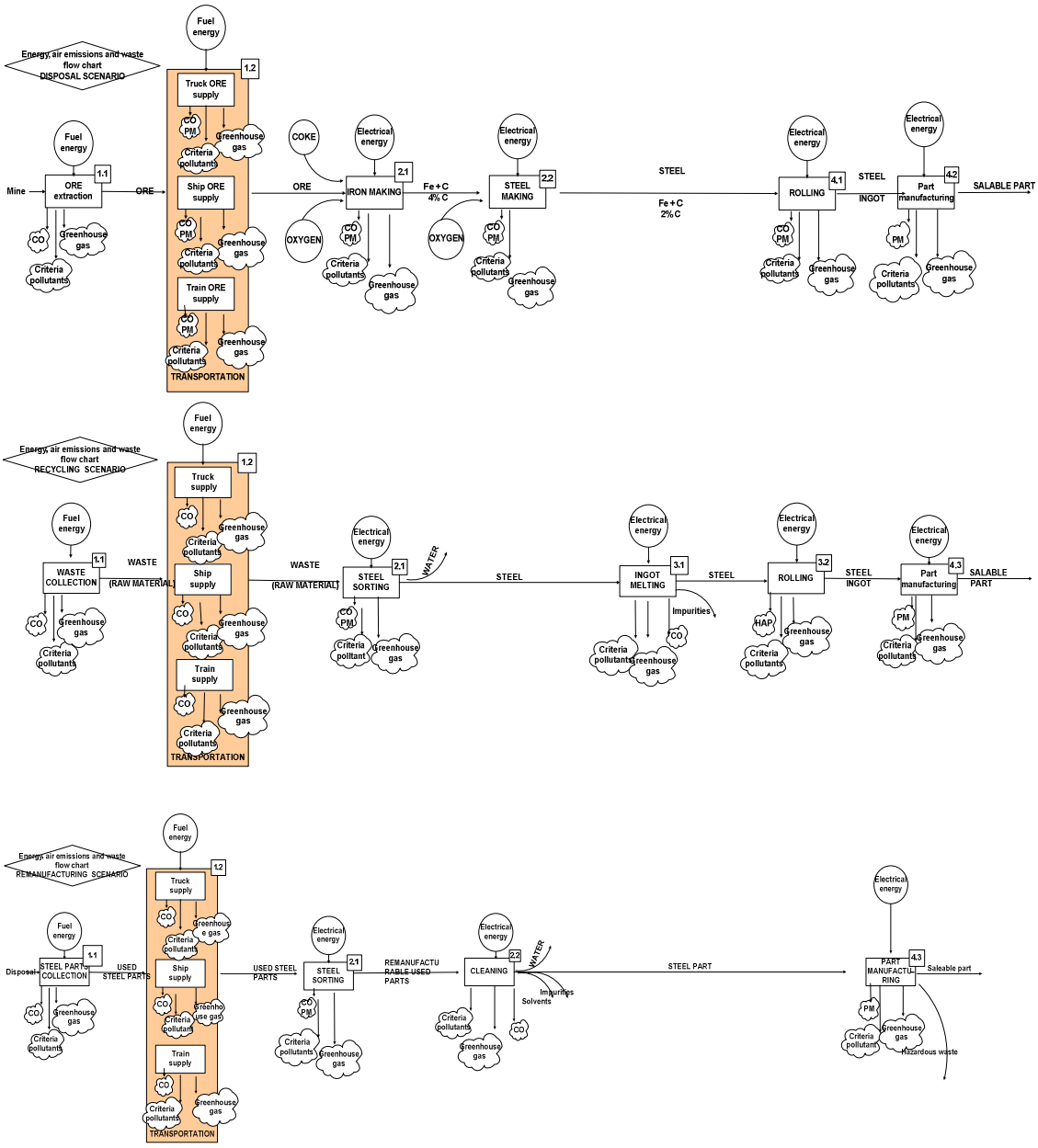


Figure 3-4 Scenarios processes for Steel gear

3.3.1 Steel gear disposal scenario (DS) description

As shown in Figure 3.4 and as all other scenarios, the steel gear disposal scenario (DS) is divided in four phases. The first phase is composed of the extraction of the steel ore at the mine followed by the ore transportation to the manufacturing plant. The

primary material is composed of iron ore (FeOx). The second phase consists in transformation of ore into pig iron and melting to produce liquid steel. The production of steel will be more detailed in Chapter 5, Section 5.1.1.2. The liquid steel resulting from Phase 2 is then directly cast in Phase 4. As in aluminum disposal scenarios, Phase 3 is empty. Whereas aluminum is ductile and moldable, steel is difficult to cast. Therefore, steel casts are usually simple shapes obtained by rolling cast processes. These cast parts might be streamlined beams, cylinders, sheets…In the case of a gear, the cast part is a cylinder. This steel particularity leads to a higher amount of material removed during the machining phase that is Phase 4.

3.3.2 Steel gear recycling scenario (RCS) description

The primary material of steel recycled parts is used steel. They are multiple sources of used steel. The most common are steel cans, cars and civil constructions such as bridges and buildings. As it will be detailed in Chapter 5, the first phase consists in collecting waste in landfills. The collected material is composed of used steel but also by glass, organics, wood, etc… The first phase ends with the transportation of this waste to the recycling plant. The second phase is composed of the sorting of the waste where used steel is separated from the other materials. During Phase 3, the used steel is molten down and is then processed by casting machines. As in Disposal scenarios, casting is followed by the machining of the part or phase 4.

3.3.3 Steel gear remanufacturing scenario (RCS) description

The first phase of steel remanufacturing scenario is the material supply. It begins with the collection of used steel gears. The steel gears are then transported to the

remanufacturing plants. The gears collected and transported might be assembled with other parts. In the second phase consists in the purification of steel parts. In a first time, it consists in disassembling, sorting and finally in cleaning the gears. Phase 3 is empty. In fact, the cleaned parts are directly sent to the machining process where the gears are refurbished to their original function, it is the final fourth part.

3.4 Transportation

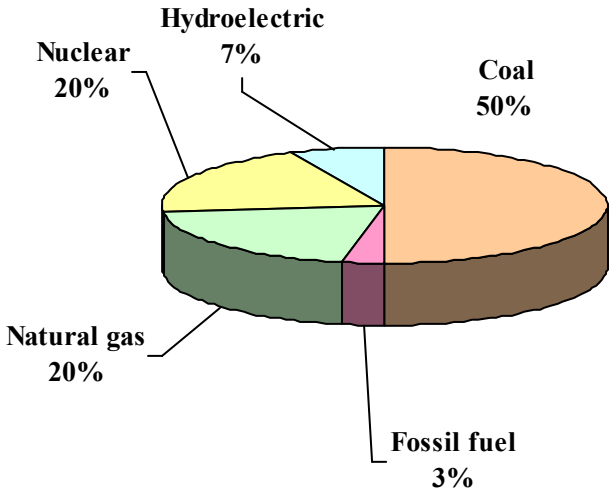
The transportation is present in the three end-of-life strategies and is indispensable to the production. In the three scenarios, parts are assumed to be entirely realized in one plant. Therefore, the transportation is necessary for the primary material supplying only. As it will be demonstrated in this study, the transportation plays a main role in end-of-life strategies environmental impact.

CHAPTER 4

US ENERGY GENERATION INVENTORY ANALYSIS

4.1 US Power generation resource

Countries power generation depend on their natural resource. The United States is a wide continent where States independently produce their energy. The resources are different and consequently the resulting pollutions are different. This is why the study will consider of a national average. The data are issued by US governmental sources such as the Energy Information Administration (EIA) and the Environmental Protection Agency (EPA). The US electrical power is generated with coal, fossil fuels, natural gas, nuclear power and water in the proportion displayed on Figure 4.1.



Fuel	Proportion [%]
Coal	50
Nuclear	20
Natural gas	20
Petroleum	3
Hydroelectric	7

Figure 4-1Electrical power generation by fuel type (EIA 2007)

4.2 Fuels energy characteristic: heating value

In addition to electricity generation, fuels are also used in other processes such as heating. Therefore, determining the characteristics of each fuel is necessary to determine the energy consumption of the three scenarios processes. The heating or energy capacity of a fuel is determined by its "heating value" which can be defined by the quantity of energy released per quantity of fuel used.

4.2.1 Coal characteristics

Coal is divided in four categories with different applications. The coal generally used for energy production is Bituminous coal (American Coal Foundation 2006). This particular coal's carbon content can rise up to 85% wt. The heating value of coal is determined by the amount of carbon because of its predominant and high heating value (14500 BTU/lb which is 9359 kWh/ton). The heating value is also inversely proportional to the amount of oxygen content of coal. In fact, oxygen present in coal oxidizes the coal's carbon and decreases its capacity to combust with the ambient oxygen and creates heat. Therefore, heating value of coal varies upon its composition. The heating value of Bituminous coal varies from 6,780 kWh/ton to 10,015 kWh/ton. A study done in Illinois gives a coal heating value of 7,500 kWh/ton which verifies the interval considered (Klara 2007). Finally governmental sources estimate coal heating value at 20,681,000 BTU/short ton which is 6,680 kWh/metric ton. This last number will be considered as a reference for the study (Energy Information Administration (EIA) 2007). To conclude, in the current work, the use of coal is strictly dedicated to energy generation.

4.2.2 Natural gas characteristics

Natural gas is generally 85% or more methane. The rest is composed of ethane, propane, butane and inert gases. The heating value of natural gas is 1,020 BTU/scf which is 10.55 kWh/cubic meter (Environmental Protection Agency 1998) (Energy Information Administration (EIA) 2007). In this study, for combustion calculations and emissions, natural gas will be assumed to be 100% methane. The methane heating value is estimated in literature at 1010 BTU/scf which is 10.4 kWh/cubic meter(McAllister 2002). The approximation of 100% methane does not influence noticeably the heating value of the fuel. The heating power of natural gas is used in electricity generation but also in heating processes such as melting processes, where the energy cost would be much higher with electrical oven than gas fired ovens. Therefore, this data will be essential in scenarios where melting of material is involved.

4.2.3 Diesel characteristics

Diesel fuels have different heating values depending on their composition. Nevertheless, a recurrent value for this energy is 139,000 BTU/gallon which is 10.8 kWh/L (Energy Information Administration (EIA) 2007). Diesel is mostly used in transportation and will be deeply discussed in Chapter 6, Section 6.2.1.

4.2.4 Heavy oils characteristics

Heavy oils are the fuel oils remaining after the lighter oils have been distilled off during refining processes of fossil fuels. Heavy oils are especially dirty. In fact they have a low ratio hydrogen carbon ratio, high content of asphalts, heavy metals, sulphur and Nitrogen. Heavy oil is very dense and viscous (Schlumberger Inc 2002). These oils

usages tend to be limited by regulations but are still used in the transportation field, mainly in the ship transportation. Given EIA data, heavy oil heating value is 5,800,000 BTU/ Barrel which are 10.7 kWh/L.

Table 4.1 summarizes the heating values that will be used in the analysis of energy consumption (Chapter 5 and Chapter 6).

Table 4-1 Fuels heating values

Fuels	Heating values	
Coal	6680 kWh/ton	6.6 kWh/kg
Natural gas	10.55 kWh/m3	
Diesel oil*	10.8 kWh/L	13 kWh/kg
Heavy oil**	10.7 kWh/L	10.7 kWh/kg

*

$\rho diesel = 0.833 kg / L$

**

$\rho heavyoil = 0.9 kg / L$

CHAPTER 5

PROCESSES ENERGY CONSUMPTION INVENTORY ANALYSIS

In the chapter, the energy consumption of the three end-of-life strategies processes will be evaluated. The first phase that is going to be discussed here is the primary material supply. However, the material transportation will be discussed in Chapter 6 and therefore will not appear in the current chapter.

5.1 Phase 1: Primary material supply

5.1.1 DS phase 1, energy consumption analysis

5.1.1.1 Aluminum DS process 1.1: Bauxite mining

Bauxite is mined with trucks. The ore is heated, crushed and grinded finely enough to be shipped and transformed into alumina in the following phase. The energy consumptions resulting from Bauxite mining found in the literature usually include transportation from the mine to the shipping point. In those studies, the energy consumption of a 0 km transportation distance **14.4 kWh/ton salable aluminum** (International aluminum institute 2004). This value will be used for the energy consumption of Bauxite. A detailed study of the transportation from the mine to the manufacturing plant will be performed Chapter 6.

5.1.1.2 Steel DS process 1.1: Iron ore mining

The processes realized in iron mines are iron ore extraction and iron ore palletizing. The main energy sources in mining are diesel fuels. The energy consumption of the extraction

is estimated at 80 000 BTU/ton which is equivalent to 26 kWh/metric ton (National energy technology laboratory 2004) (Outo Kumptu 2005) (Metso minerals 2007). The second process usually present on the mine site is the Pelletizing. This process turns iron grains into balls also called pellets. The Iron content of such pellets is estimated between 60 and 70% (Outo Kumptu 2005). Pelletizing energy consumption is estimated around 12 000 BTU/ton Iron ore produced, which is equivalent to 4 kWh/metric ton Iron ore (National energy technology laboratory 2004). The overall energy consumption of steel mining is therefore around **30 kWh/metric ton Iron ore.** (Outo Kumptu 2005) (Metso minerals 2007).

5.1.2 RCS and RMS, phase 1, energy consumption

5.1.2.1 Steel and aluminum RCS and RMS, process 1.2: Used material collection

Steel and aluminum used parts collections phase is mainly composed of transportation and therefore will be discussed in Chapter 6.

5.2 Phase2: Material purification

This section begins with Disposal scenarios phase 2. Recycling scenarios phase 2 will follow and finally, remanufacturing scenarios phase 2 will close this section.

5.2.1 DS phase 2, energy consumption analysis

Figure 5.1 illustrates aluminum disposal scenarios phase 2. It will be referenced in the following section.

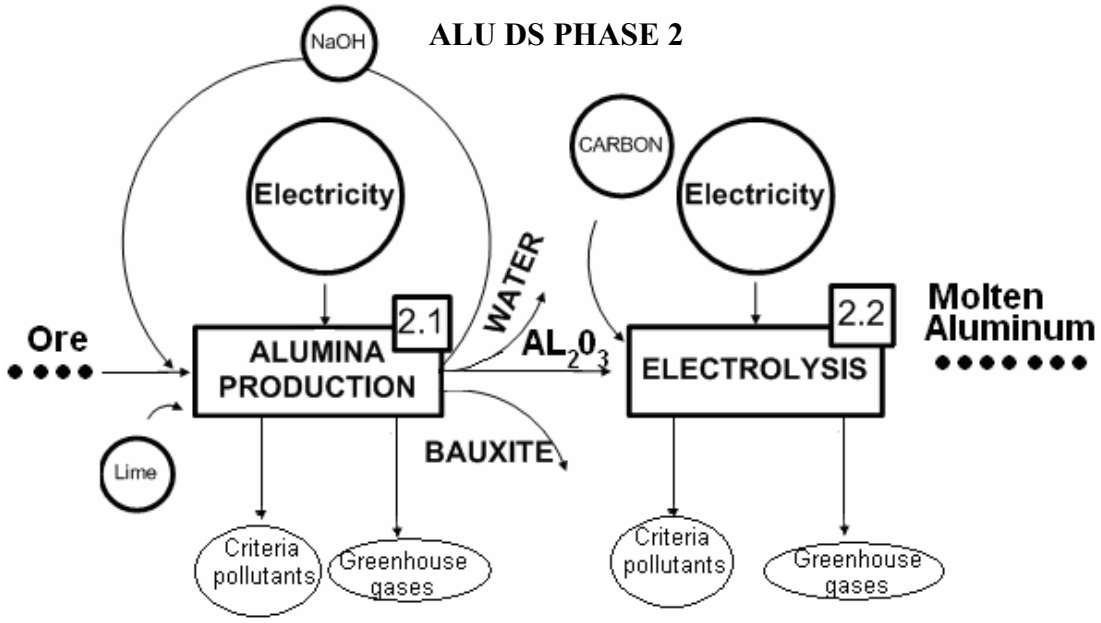


Figure 5-1 Aluminum transfer case DS Phase 2, processes analysis

5.2.1.1 Aluminum DS process 2.1: Alumina production

In the disposal strategy, alumina production is the first process of the purification phase (phase 2). This process transforms bauxite into alumina (Al_2O_3) using the Bayer process (1888) (Britannica Encyclopedia Inc 2007). This process consists in four main steps. These steps are detailed Figure 5.2. Chemical, mechanical transformations and heating processes are involved.

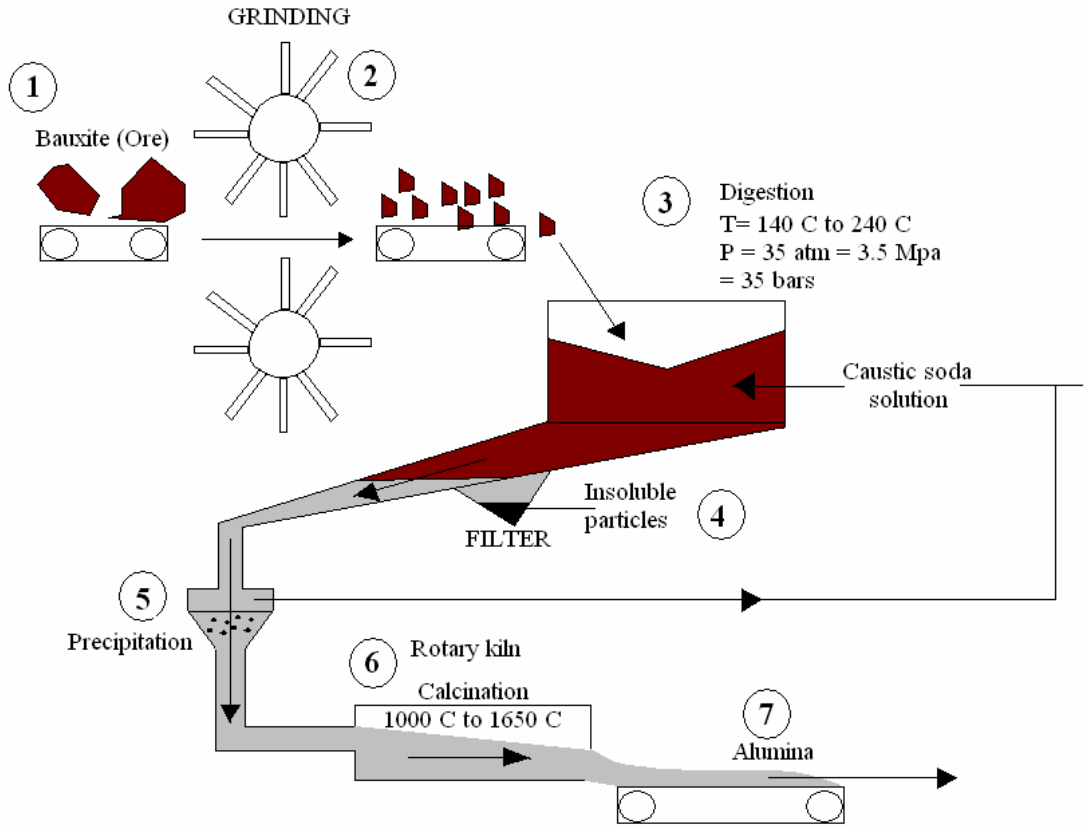


Figure 5-2 Alumina production (International aluminum institute 2007)

In the current work, a detailed calculation of each process energy consumption would have been inefficient given the data already existing (Choate 2003) (International Aluminum Institute 2000). Thus, the energy consumption of this phase is determined thanks to literature data. The energy consumptions and the fuels used in alumina production are given Table 5.1. The fact that 2 kg of alumina are necessary to produce 1 kg Aluminum has been considered in the calculations.

Table 5-1 Alumina production energy consumption (EIA world aluminum)

Fuels and Electricity	*Wt. mean*	*Unit*	*Energy kWh/ton Alumina*	*Energy kWh/ton sal. Aluminum*
Heavy oil	154	kg/t	1817	3634
Diesel oil	1.7	kg/t	22	44
Gas	222	m3/t	2220	4440
Coal	374	kg/t	2618	5236
electricity	170	kwh/t	170	340
Total			**6847**	**13694**

The most energy consuming processes are the dissolution of ore into sodium Aluminate and the final calcinations resulting in pure alumina. These processes need respectively heating temperatures of 270C and 1300C. Those heating phases are mainly powered by gas and coal (International aluminum institute 2006) (International Aluminum Institute 2000). Another study issued by the US energy Department of energy gives different results (Choate 2003). In fact, surveys on aluminum plants allowed a rough estimation of 7500 kWh/ton salable aluminum for alumina production. One interesting outcome of this governmental study is the calculation of the theoretical energy requirement of alumina production that is 130 kWh/ton salable aluminum. This low value is far from the actual results and might explain the differences between the value in Table 5.2 and the 7500 kWh/ton aluminum resulting from industrial surveys. Another survey performed for the US energy department in 1997, determined an energy requirement of 13760 kWh/ton salable aluminum for alumina production (Energetic Inc 1997). This value is close to the energy consumption calculated in Table 5.1. Therefore, the alumina production energy consumption of **14000 kWh/ton salable aluminum** will be used.

5.2.1.2 Aluminum DS process 2.2: electrolysis

The electrolysis energy consumption was determined with calculation and was validated by governmental data. The parameters necessary to perform electrolysis are summarized in Table 5.2 (Hartman 1992).

Table 5-2 Electrolysis parameters

Parameters		Value
Bath temperature	Tc	920C to 980C
Electrical current in the resistances	I	180 000 A
Voltage	U	4.5 V

The energy consumption of the electrolysis process for one day EN_{EL24} is given by Equation 5.1.

$$EN_{EL24} = U \times I \times 24 = 4.5 \times 180000 \times 24 = 19{,}440{,}000 \ Wh/day \quad [5.1]$$

First Faraday law will be used to determine the energy necessary to produce 1 ton of aluminum. This law is defined as follow:

"The amount of any substance deposited by the current is proportional to the quantity of electricity flown through the electrolyte. The amounts of different substances deposited by the same quantity of electricity are proportional to their chemical equivalent weights." (Livingston 1905)

The total charge involved in one day of aluminum electrolysis is given Equation 5.2:

$$Q_{ALU} = I \times t = 180{,}000 \times 60 \times 60 \times 24 = 155 \cdot 10^8 C \quad [5.2]$$

Considering that the charge of an electron is given by the Faraday constant *F = 96500 C/ Mol* and according to the first Faraday law, the amount of electrons passing through the circuit and corresponding to the total charge Q_{ALU} is given Equation 5.3:

$$\xi_{ALU} = \frac{Q_{ALU}}{F} = \frac{155 \cdot 10^8}{9.65.10^4} = 161{,}161 moles\ e^- \quad [5.3]$$

Given the fact that 3 moles of electron reduces on mole of Aluminum and given the molar mass of aluminum M_{ALU}=27 g/mol, the daily production of aluminum η_{ALU} is given Equation 5.4.

$$\eta_{ALU} = \frac{\xi_{ALU} \times M_{ALU}}{3} = 1.4 \cdot 10^6\, g = 1.4 \text{ tons aluminum/ day} \quad [5.4]$$

Given the efficiency E of the process, the energy consumption rate can be eventually calculated thanks to Equation 5.5.

$$EN_{EL} = \frac{EN_{EL24}}{\eta_{ALU} \times E}[Wh / tonSalableAlu] \quad [5.5]$$

The energy consumption resulting from Equation 5.5 are given in function of the efficiency of the process Table 5.4.

Table 5-3 Energy consumption in function of electrolysis efficiency

EN EL24 [kWh/day]	19440		
η_{ALU} [tons/day]	1.4 tons/day		
Efficiency E	70%	90%	100%
EN el [kWh/ton]	19835	15420	13885

In Table 5.3, considering a total reaction, electrolysis energies is 13,885 kWh/ton. Electrolysis energy consumptions are given Table 5.3 for different reaction efficiencies. A study issued by the U.S. Department of Energy estimated electrolysis energy consumption at 15000 *kWh/ton salable aluminum(Choate 2003)*. Another study driven by academics of the National University of Singapore performed a survey on 4 different aluminum plants and determined an electrolysis energy consumption between 15 000 *kWh/ton salable* aluminum and 16 000 *kWh/ton salable aluminum (Tan 2003)*. Given the coherence of the calculations confronted to the literature, the energy requirement for aluminum electrolysis will be estimated at **15000 kWh/ton salable aluminum.**

Figure 5.3 illustrates steel disposal scenarios phase2. This figure will be a reference in the section.

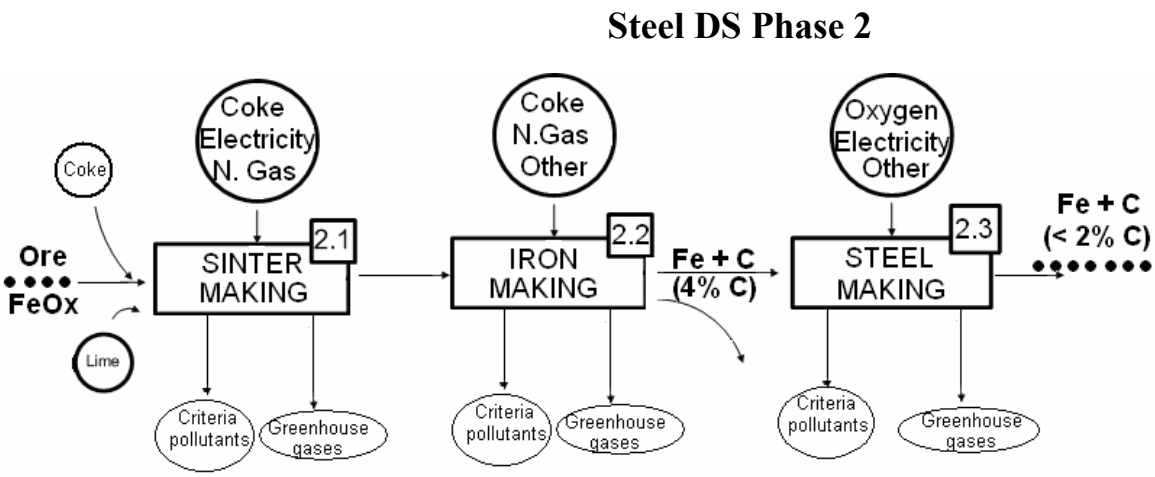


Figure 5-3 Steel gear DS phase 2 process analysis

Steel results from the association of iron and carbon. Figure 5.1 is the iron carbon diagram. It shows the physical state of different alloys iron-carbon (Fe + C) in function of the temperature and the amount of carbon.

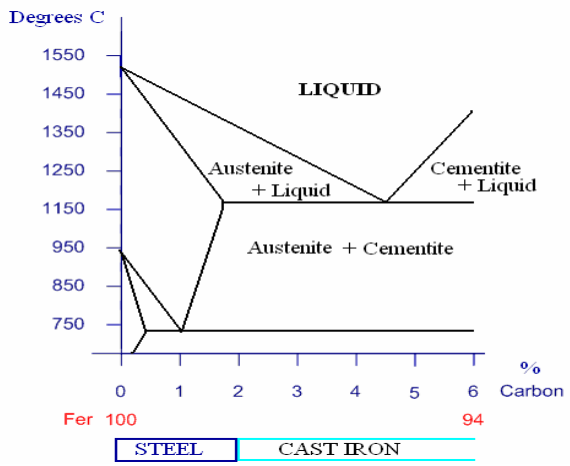


Figure 5-4 iron-carbon diagram

As shown Figure 5.4, steel content of carbon is less than 2%. The melting temperature is located between 1400 C and 1550 C. Steel producing is a significant activity in the US. In fact, 2 to 3 % of the US energy consumption is dedicated to this specific domain (Energetics Inc. for US Department of Energy 2000) and 13 % of the world global production comes from this US. This level of production places the country at the fourth position after Western Europe, China and Japan (Energetics Inc. for US Department of Energy 2000). Steel results from the chemical reaction of iron ore associated with limestone and coke. Steel making is composed of two successive processes that are iron making and steel making. Coke is necessary to refine iron. Coke making consists in transforming coal into coke via high temperature calcinations rising up to 1100C in the absence of oxygen (American Iron and Steel Institute 2007; Steel authority of India limited 2007). However this process is high energy consuming and highly polluting it will not be considered in the environmental impact analysis. In fact, given the assumptions made in the current this study, energy sources and additives processing are out of study boundary. This is why, the first process that is going to be

studied is the Iron making. Significant progress has been done in the last 50 years in the steel production energy saving. In fact, the energy consumption rate has dropped from 14650 kWh/ton steel shipped (45 MBTU/ton) to 5860 kWh/ton (18 MBTU/ton) in 2005 (Figure 5.5). This is why, it is important to consider the latest data available, at least data after 1990 where the slope of energy consumption rate is not as steep as before.

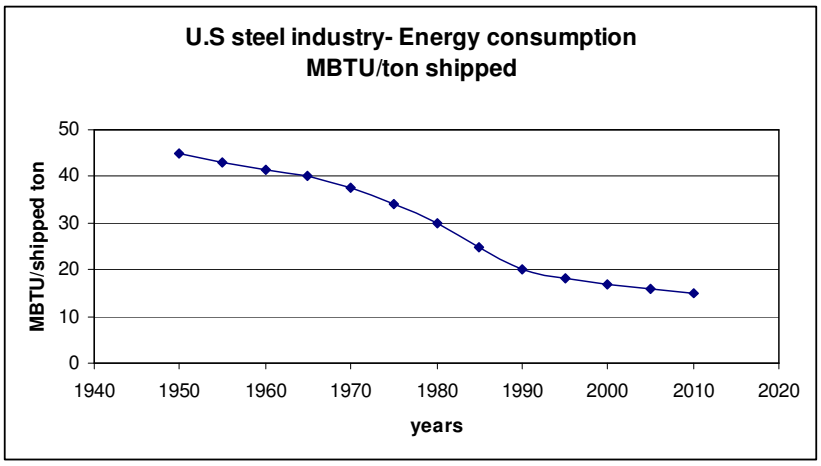


Figure 5-5 US Steel industry energy consumption rate from 1950 to nowadays (Stubbles 2000)

5.2.1.3 Steel gears DS phase 2.1: Sinter making

Iron making consists in reducing at high temperature the natural Iron Ore (FeOx) into Iron and Carbon (Fe + C) by injecting hot air (source of oxygen), pure carbon resulting from coke making process and limestone. The Iron ore that enters the conveyor belt is shaped like pellets. These pellets are usually processed before shipping, on the mine site, they are made of Iron ore and binders. The following process in the Iron making is Sintering. Iron ore, water, Coke (5%) and Limestone blend are carried on a conveyor belt

through a high temperature (1300 C to 1500C) flame created by the heat and injected air (Energetics Inc. for US Department of Energy 2000). In this process, the carbon present in the coke burns with the oxygen brought by the air input (European Commission 2007). The resulting mixture is called Sinter. 2.5 tons of raw material, coke, limestone and water are necessary to create 1 ton of Sinter. The energy consumption of this phase is evaluated in the literature to be around 28 PJoules for 12.1 Mtons Sinter produced, which is equivalent to 640 kWh/ton Sinter. This value was calculated for the year of 1994 (Enerst Orlando Lawrence Berkeley National Laboratory 1999). This result is confirmed by a governmental report where the sintering energy is evaluated at 1.55 10^6 BTU / ton sinter which is 500 kWh/metric ton Sinter (Energetics Inc. for US Department of Energy 2000). Therefore, given those two results, 600 kWh/ton Sinter will be considered as a valuable approximation of Sinter process. Assuming that 0.22 tons Sinter are necessary to produce 1 ton Iron (Energetics Inc. for US Department of Energy 2000) and that 1.03 tons Iron are necessary to create 1 ton steel, this energy is equivalent to **136 kWh/ton steel**. 77% of the energy used in the process results from coke breeze, 3% comes from Natural gas combustion and 20 % results from electricity (Energetics Inc. for US Department of Energy 2000). These proportions are summarized Table 5.1.Coke breeze heat used in this process mainly comes from the coke making process. Traces of other fuels added during the sinter process might be counted in these 77 %. Nevertheless, in this study, because of the lack of precision and information about the exact proportions, 77% pure coke will be considered here.

Table 5-4 Type of fuel used in Sinter making (Energetics Inc. for US Department of Energy 2000)

Fuel	Proportion over total energy consumption
Coke	77
Natural gas	3
Electricity	20

5.2.1.4 Steel gears DS phase 2.2 Pig iron making

Iron ore pellets, Sinter and coke are then carried to the blast furnace where temperature rises up to 1560 C to produce Pig Iron (UK Steel 2007) (Energetics Inc. for US Department of Energy 2000). Iron pellets are produced at the mine and will be discussed in the section dedicated to mining analysis (Chapter 6). The composition of Pig Iron is given Table 5.6. In 1998, 1.3 tons of Iron pellets with 0.22 tons Sinter were used to produce 1 ton Pig iron.

Table 5-5 Pig Iron composition (Energetics Inc. for US Department of Energy 2000)

Component	%
Carbon	4 to 4.5
Silicon	0.3 to 1.5
Manganese	0.25 to 2.2
Phosphorus	0.04 to 0.20
Sulfur	0.03 to 0.8
Iron	90

The molten pig iron is collected from the bottom of the Furnace. The impurities float at the top of the molten Iron and are therefore easily removed. The energy consumption of this phase is given thanks to literature data. For the 1994 year, The consumption was estimated at 680 PJ for 49.9 Mtons Iron produced with a blast furnace, this is equivalent to 3820 kWh/ton Iron molten (Enerst Orlando Lawrence Berkeley National Laboratory

1999). This value is confirmed by the governmental data, where Blast furnace energy consumption is 12.1 10^6 BTU/ton Iron which is equivalent to 3940 kWh/metric ton Iron molten. The energy necessary to produce Pig Iron with a blast furnace is therefore evaluated at 3900 kWh/ton Pig Iron which drives to an approximate energy consumption rate of **4000 kWh/ton steel.** During the sintering and the Blast furnace melting, the combustion of Carbon with oxygen results in large amounts of CO that is further used for heating purpose. In this process, the main fuels used are Coke, Natural gas and coal. The proportions are given Table 5.7.

Table 5-6 Type and proportions of fuel consumed in Pig iron making (Energetics Inc. for US Department of Energy 2000)

Fuels in Blast furnace	Proportion in %
Coke	67
Natural gas	11
Coal	9
Blast furnace gas	6
Other (Electricity, Oxygen...)	7

5.2.1.5 Steel gears DS phase 2.3: steel making

As mentioned before, Pig Iron coming out of the Blast furnace has a Carbon content of 4%. Steel making consists in injecting oxygen into Pig iron to reduce the carbon quantity to a maximum of 2%. Two different processes are currently used to make steel. One makes use of a Basic Oxygen-Furnace Process often called the BOF. In this process, Pig Iron associated with Scrap metal (20 to 25 % of scrap) are used as primary material. Another process using Electrical Arc Furnaces more often called EAF are

charged only by scrap metal (Environmental Protection agency 2007). In 1997, 44% of the steel production is made with EAF processes. In 1999, 46 % of the steel production is made with EAF processes (Energy Information Administration 2007). In 2001, the EAF production rises to 47.5 % of the global steel production (Environmental Protection agency 2007), which means that almost half of the steel commercialized is issued by recycled Iron and steel usually collected from buildings, bridges and car disposals.

It is important to notice that BOF are self-generating heat source. In fact, the heat is generated by the pure oxygen blown on the metal. Oxygen combusts with Carbon but also with the Silicone, phosphorus and the manganese present in the Pig Iron. These exothermic reactions produce high temperature that can rise up to 1700 C (Britannica Encyclopedia Inc 2007). These reactions with Oxygen result in a high level of dust, sludge and Slag (Environmental Protection Agency 2007). In order to control exhaust gas temperature and humidity levels, high quantities of water are also used during this process. All these wastes will be discussed in Chapter 8.

As mentioned before, BOF uses 70 to 80% of molten Iron and up to 20 % to 30% of scrap. The energy consumption of BOF was estimated for the year of 1998 between 0.9 MBTU/ton (290 kWh/metric tons) and 1.2 MBTU/ton (390 kWh/metric tons) depending on the fuels injected (Natural gas, Lime etc…) (Energetics Inc. for US Department of Energy 2000) (Stubbles 2000). Therefore, in the current study, the energy requirement for a BOF is estimated at **350 kWh/metric ton Steel**. This result does not consider the hot metal energy release because the energy was already considered in the previous step. An approximate repartition of the energy sources are determined Table 5.8. The sources that are mostly used in the basic oxygen furnaces are electricity, oxygen. The

other sources are mainly additives to help chemical reactions, exhausts. They might be natural gas, coke, coal, lime etc…Because of the different assumptions made in literature; an equal repartition of the sources is done in this study.

Table 5-7 Energy sources repartition

Fuel	Proportions
Oxygen	1/3
Electricity	1/3
Other	1/3

The other way to produce steel is to use electrical arc furnaces (EAF). In general, these furnaces are charged with 100% scrap (Bluescope steel 2007) (Stubbles 2000) and are therefore used for recycling purposes. This particular melting process will be studied in the appropriate section (5.2.2 b) steel RCS process: used steel melting)

5.2.2 RCS phase 2, energy consumption analysis

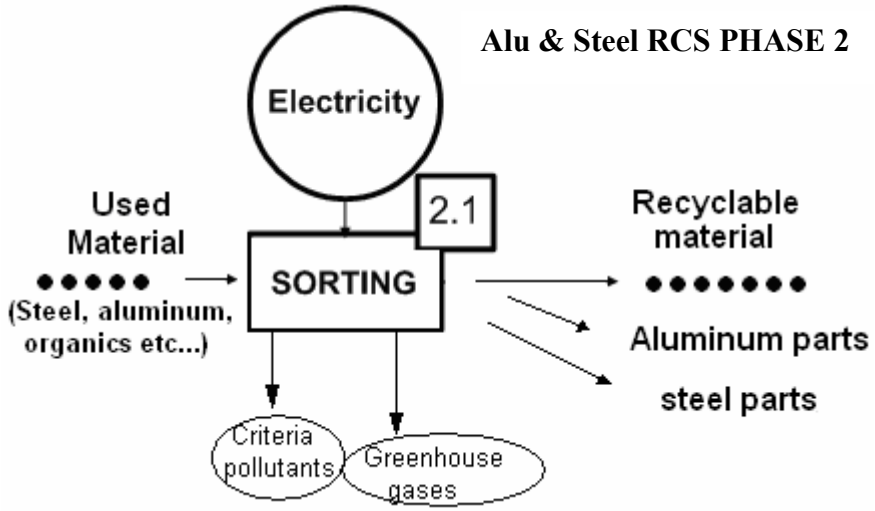


Figure 5-6 Aluminum transfer case Phase 2 process analysis

5.2.2.1 Aluminum transfer case and steel RCS process 2.1: material sorting

In recycling scenarios, phase 2 is composed of material sorting (Phase2, Sub-phase2.1). This sorting process is also present in remanufacturing cycles but the parts sorted are different. In fact, recycling sorting outcome is composed of different parts of aluminum whereas remanufacturing output is composed of one type of remanufacturable parts (transfer cases housing or steel gear in the case of the current study). The sorting process follows the collection phase. This separation phase has different protocols depending on the type of waste processed and its origin. These different wastes are divided in three categories: the municipal waste, the industrial wastes and the "end-of-life vehicles".

Municipal waste management

The municipal wastes are presorted wastes that are collected periodically by the city waste management at private houses and are recycled. A visit at a Georgian recycling facility lead to the following composition and entry rates of the waste:

Table 5-8 Georgian recycling plant waste rates characteristics

Waste arrival per day	lbs
Paper	40,000
Plastic	1500
PET	3000
Steel	1000
Alu	800
Glass	30,000

In order to evaluate the energy consumption of waste sorting, a Georgia plant records have been evaluated and taken as reference. The monthly electrical consumption dedicated to waste sorting has been determined thanks to personal communication with

the recycling company employees. This bill is 51 480 kWh/month with a 75 short tons/day sorting rate. This leads to an estimation of 25.55 kWh/ton sorted waste (23kWh/short ton sorted waste). As it is shown Table 5.8, the mass proportion of aluminum in the total waste is 1% wt and the proportion of steel is 1.3% wt. For this particular energy consumption calculation, steel and aluminum are considered independently. Therefore, in the case of aluminum sorting, 1 metric ton of sorted waste contains 100 kg of Aluminum. Therefore, in order to get 1 metric ton aluminum, 10 tons waste have to be sorted and therefore, **2555kWh/ton salable aluminum** (2300 kWh/short ton salable aluminum) energy have to be consumed. With the same considerations, in the case of steel sorting, 1 metric ton of waste sorted contains 130 kg of steel. Therefore, 1 metric ton of steel sorted consumes **1965 kWh/ton salable steel** (1769 kWh/ton salable steel). The consideration of steel and aluminum resulting from one same ton of waste would decrease the energy consumption of sorting processes. This could be done in a future research. Here the cases are studied independently. In the reuse scenarios such as recycling and remanufacturing, secondary aluminum is assumed to come mostly from municipal waste, whereas steel has three equivalent origins which are municipal waste disposal but also used car disposals and industrial disposals.

End-of-Life car

Recycling disposed cars has become a current process. In fact, “automotives are the most recycled consumer product”. Steel content in a car is 77% of the total mass. The same proportion of steel is assumed in the end-of-life car site. By comparing the yearly recycled steel from automobiles to the steel used in automobiles, automobiles have a steel recycling rate close to 100% (Recycle Steel Organization 2007). Therefore, for steel

purpose, the end-of-life car waste management will be considered as a significant source of used material.

Industrial waste

The industrial waste is composed of “new scrap” which is material waste from manufacturing plants. This material has a life time equal to zero and has never served. The “new scrap” is in opposition to the “old scrap” such as used cars, cans and consumption goods. Waste such construction materials are also part of industrial waste.

As aluminum is assumed to have a single origin of Municipal waste, Steel is assumed here to come equally from the three waste categories

The last waste management considered here includes all types of landfills collecting unsorted waste from residences, businesses, contractors and public entities. Three main processes are assumed to be used for ferrous-sorting purpose in these landfills. They are shredding, magnetic separation and balling.

The shredding system has many applications, with different operation frequencies and powers. Nevertheless, it is possible to determine an interval of energy requirement varying from **11 kWh/ton entering waste to 40 kWh/ton entering waste**, with shredding rates of 15 tons of waste shredded /hour (Manouchehri 2006) (Eurobalers LTD 2006) . In this study, scrap is assumed to go through one single shredding process. The magnetic separation of ferrous materials is assumed to be performed by magnets. These magnets have power varying generally from 3 kW to 20 kW, but might rise up to 40 kW depending on the maximum lifting capacity required (Dynaset 2007) (GENSCO 2007) (Skid Steer 2006). Table 5.4 gives an extract of magnets power properties. The resulting power rate is evaluated at 0.55 kW/metric ton steel lifted. In a study dedicated to

electrical circuits recycling, magnetic energy requirement is estimated to be 0.6 kWh/ton and shredding is estimated at 60 kWh/ton. This indicates that magnetic energy requirement is 100 times less than shredding energy requirement. Therefore, given the fact that shredding phases have been estimated between 11 kWh and 40 kWh, the magnetic energy requirement should vary between 0.11 kWh/ton lifted and 0.4 kWh/ton lifted. The energy consumption of the magnet is therefore considered to be 0.4 kWh/ton. This corresponds to a coherent 43 minutes lifting labor per ton of steel. Because of lack of examples and information, the transportation energy consumption in this phase is not considered.

Eventually, the baling process consists in compressing sorted material for stocks or transportation to other processes. This phase energy consumption has been evaluated thanks to the machine sold on the market and used in the industry. Table 5.10 shows the specification of such machines found in different retailers catalogues. The general configuration assumption for the current study is a 150 kW machine (200HP), with a output mass rate of 50 tons/hour. These assumptions are coherent to the machines found on the market and drive to an energy consumption rate of 3 kWh/ton material baled.

Table 5-9 Baling machines specification (Eurobalers LTD 2006) (Marathon Equipment 2007) (Harris Corporation 2007)

Machine	Power	Output bale capacity	Cycles bales/hour	Output rate kg/hour	Energy consumption rate
TGS-101-2 high compression	2 * 90 kW or 2* 120 HP	100 kg [0.35m*0.35m*variable]	120	12000	15 kWh
Harris TGS-100 baling press	2*75 kW or 2* 100 HP	145 kg [0.3*0.3*variable]	128	18560	8 kWh
blockPak 3000	93.2 kW or 125 HP	[2.1m*2.1m*variable]		81648	1.1 kWh
Harris HRB-1035 W	140 HP to 200 HP or 105 kW to 150 kW		165 to 240	25000 to 60000	2.5 kWh to 4.2 kWh

Steel scrap is collected in end-of-life car sites, municipal waste recycling site and industrial landfills. The energy consumption involved in theses places are summarized Table 5.10.

Table 5-10 Sorting energy consumption by site and by process

Sorting site	PMW	ELC	Industrial land fill
Energy rate	23 kWh/ton sorted	Shredding = 40 kWh/ton sorted	
		Magnet = 0.4 kWh/ton steel	
		Baling = 4kWh/ton baled	

In order to determine the composition of landfills, government and companies' data were used. In these studies, different types of landfills are studies. Some of them have only residential collections circuits (transfer stations), while other landfill have residential, commercial and industrial waste origin. Steel content in presorted municipal waste plants (PMW) is 1 %. On the other steel content appears to be between 2.5 and 4% wt in landfills where no presorting has been realized (California Integrated waste management Board 2007) (Cascadia Consulting Group Inc 2001). The highest steel contents are

usually found in the landfills where waste is collected in businesses, especially in industrial machinery plants, production plants, construction sites, etc… (California Integrated waste management Board 2007). The resulting energy consumption of steel is given table 5.11.

Table 5-11 Steel sorting energy consumption by waste disposal

Waste sorting site	Steel content	Energyconsumption kWh/ton steel sorted
PMW	1%	1150
Used cars	77%	56
Landfills	4%	1004.4

In the landfills case, the shredding phase consumes 1000 kWh/ton steel and is the most energy consuming process in the sorting of steel. In this study, recycled steel is supposed to be collected equally in the three different waste sorting sites. Therefore the overall energy consumption of steel is given by Equation 5.7

$$ENsteelsorting = 1150 * 0.33 + 56 * 0.33 + 1004.4 * 0.33 = 730 \text{ kWh/ton sorted steel} \quad 5.7]$$

5.2.3 RMS phase 2, energy consumption analysis

Figure 5.7 illustrates phase 2 of steel and aluminum remanufacturing scenarios. This figure will be referenced along the section.

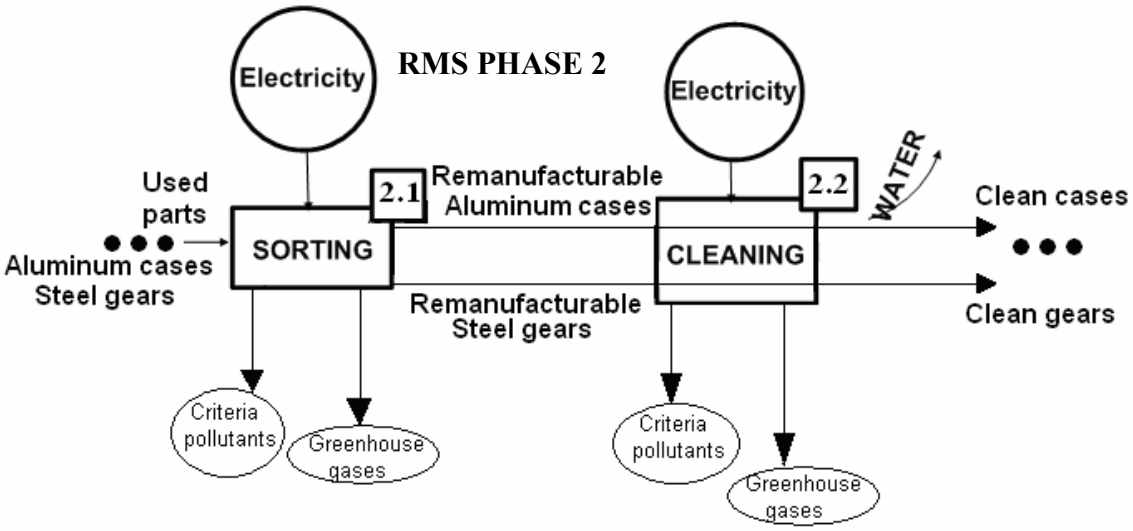


Figure 5-7 Remanufacturing scenario phase 2

5.2.3.1 Aluminum and steel RMS process 2.1: parts sorting

In remanufacturing end-of-life strategies, remanufacturable transfer case housings vary. The parameters that determine this rate are shipping policies that determine if housings are sent assembled with the transmission and other parts and also the use. Cracks and other failures might make the part not remanufacturable. In the case of small productions, the inspection is mainly visual. In most of the cases, the most energy consuming process is the non destructive disassembly of the parts. The best case would be related to a waste made of 100% remanufacturable aluminum housing cases. The worst case would be a waste composed of whole transmission with defective and non remanufacturable housing cases. For a higher level of production and with concern to diversification of remanufacturing strategies, a systematic inspection by X-ray and weighting might be necessary**.** These concerns are important and should be the object of a deepened study. Given the global objective, the sorting phase will be assumed to be as

energy consuming as recycling scenarios sorting which corresponds to an energy consumption of **2555 kWh/ton salable aluminum** and **1965 kWh/ton salable steel.**

5.2.3.2 Aluminum and steel RMS process 2.2: parts cleaning

Before beginning the study of cleaning processes, it is important to determine the domain of applications and the assumptions made in this section about cleaning processes. In fact, Cleaning can be realized by many different processes. Each of these processes makes use of different solutions such as chlorinates, fluorinated, aqueous and other cleaning agents. The environmental impact study of these solvents will be performed Chapter 7. This section will study four processes using different technologies that are ultrasonic cleaning, water cleaning spraying, solvent vapor degreasing and CO_2 blasting. The first process studied is the ultrasonic cleaning. This process has been developed recently. Its use has been successfully spread to the cleaning industry. The parts is immerged in the solution and cleaned thanks to mechanical vibration and warm temperature (55C). The second process is CO_2 blasting. This process makes use of solid CO_2 pellets projected on the dirty surface. This is also a recent expending technology. The third process will be the water cleaning spray. This process consists into spraying dirty surface with high pressured water. Finally, vapor degreasing machines will be studied. This diversity will help to get an idea of the actual energy consumption and environmental impact of cleaning processes. Other assumptions concerning the cleaned parts are also necessary to determine to make the Remanufacturing cleaning phase possible. The following assumptions concern geometrical properties of the case studies: the Aluminum transfer case and the steel gear (Figure 5.8 & 5.9).

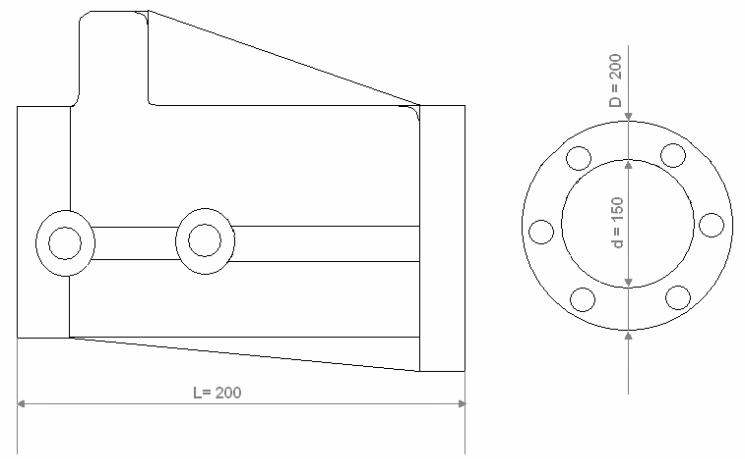


Figure 5-8 Aluminum transfer case housing

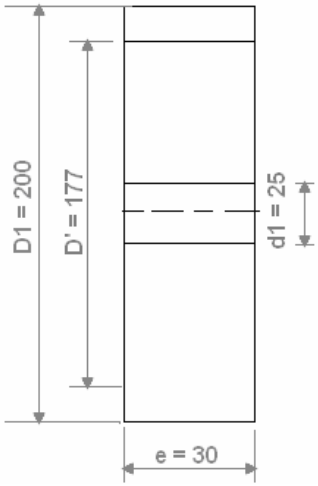


Figure 5-9 Steel gear dimensions

- Assumption on the envelop volume

This term determines the space occupied by the part. This volume is different from the parts volume. In fact, the envelop volume does not consider any cavity or other detail of the part. The envelop volume of a prismatic part can be explained mathematically as the minimum prism capable to contain the part. The aluminum transfer case envelop volume $V_{alu\,e}$ is given Equation 5.8.

$$V_{alue} = 200 \times 200 \times 200 = 8000000 \text{ mm}^3 = 8\text{L} \quad [5.8]$$

The steel gear envelop volume $V_{\text{steel e}}$ is the minimum volume of a cylinder capable to contain the steel gear (Equation 5.9).

$$V_{steele} = \pi \times \frac{D1^2}{4} \times e = 3.14 \times 100^2 \times 30 = 0.942 mm^3 \cong 1L \quad [5.9]$$

For the following cleaning machine energy consumptions calculations, the parts volumes used will be the envelop volumes calculated in Equation 5.7 and Equation 5.8. The next paragraph gives a detailed definition of the cleaning "cleaning surface" that will be further used.

- Assumption on the cleaning surface

The cleaning surface is the total part's area that has to be cleaned. The aluminum transfer case and steel gear's cleaning surface (respectively $S_{\text{alu cl}}$ and $S_{\text{steel cl)}}$ are given Equation 5.10 and 5.12.

$S_{\text{alu cl}} =$

$$2 \times \pi \times (\frac{D_1}{2} + \frac{D_2}{2}) \times L + \pi \times (\frac{D_2}{2} - \frac{D_1}{2}) \times 2 = 2 \times \pi \times (\frac{150}{2} + \frac{200}{2}) \times 150 + \pi \times (\frac{200}{2} - \frac{150}{2}) \times 2 \cong 164881 \text{mm}^2 \cong 0.16 m^2$$

$$= 0.16 \text{ m}^2 = 1.7 \text{ ft}^2 \quad [5.10]$$

In the case of gears, the teeth surface determined Equation 5.11. The gear's tooth profiles are equilateral triangles. These triangles are 11.5 mm high and have a 15 mm base as it is illustrated Figure 5.10.

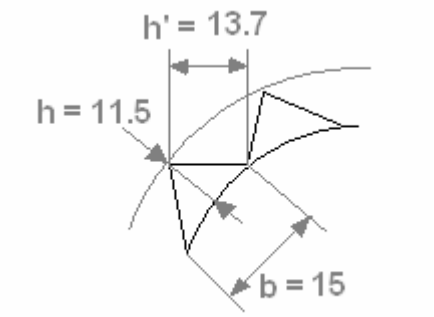


Figure 5-10 Gear's teeth profile

The surface of one tooth is 822 mm^2 (Equation 5.11).

$$S\ tooth = h' \times e = 13.7 \times 30 \times 2 = 822\ mm^2 \quad [5.11]$$

The gear studied here has 37 teeth. Consequently, the total teeth surface is 304.14 cm^2.

Equation 5.12 gives the total surface of a gear that needs to be cleaned.

$$S_{steel\ cl} = \pi \times e \times (2 \times \frac{d_1}{2}) + 2 \times \pi \times (\frac{D'^2}{4} - \frac{d1^2}{4}) + 30414 \quad [5.12]$$

$S_{steel\ cl} = 3.14 \times 30 \times (2 \times 12.5) + 2 \times 3.14 \times (88.5^2 - 12.5^2) + 30414 = 80974\ mm^2 = 0.08\ m^2$

$S_{steel\ cl} = 0.08\ m^2 = 0.86\ ft^2$

Ultrasonic cleaning machines

The parts cleaned are transfer case housings and steel gears. The contaminant that has to be removed is assumed to be rust, dust oils and grease. Phone contacts with hotlines of ultrasonic companies (Ultrasonic international) helped to certify that optimum ratio between part volume and solution volume is assumed to be 1 to 3. For the size and the dirt of the case studies, ultrasonic baths and warm temperature bath (55C) are assumed to be 15 minutes long (in general cleaning times vary from 5 to 30mins). The energy delivered to the bath is dedicated to heat the solvent, this energy is assumed to be

produced by electrical resistances as in the ultrasonic bath, is dedicated to produce electrically different pressures in a frequency range of 25 to 40 kHz.

In order to calculate the average energy of ultrasonic cleaning, specifications of machine of different capacity are going to be used. The size, the ultrasonic power and the heating power of 3 machines of the constructor R.K. Transonic are determined Table 5.12.

Table 5-12 Ultrasonic machines power specifications

	Tank capacity (L)				
	8	21	92	236	450
Ultrasonic power (Watts)	250	600	1000	2400	4800
Heater power (Watts)	500	1200	3000	5000	10000
Total (Watts)	750	1800	4000	7400	14800

The following table 5.13 gives ultrasonic power per volume of solution. The calculation considers the fact that 2/3 of the tank volume is actually occupied by solution. Figure 5.10 illustrates the power rate consumption resulting from Table 5.13.

Table 5-13 Ultrasonic power rate

	Tank capacity (L)				
	8	21	92	236	450
Solution capacity (L)	5.3	14	61.3	157.3	300
Power rate (Watts/L solution)	140.7	128.5	65.2	47	49

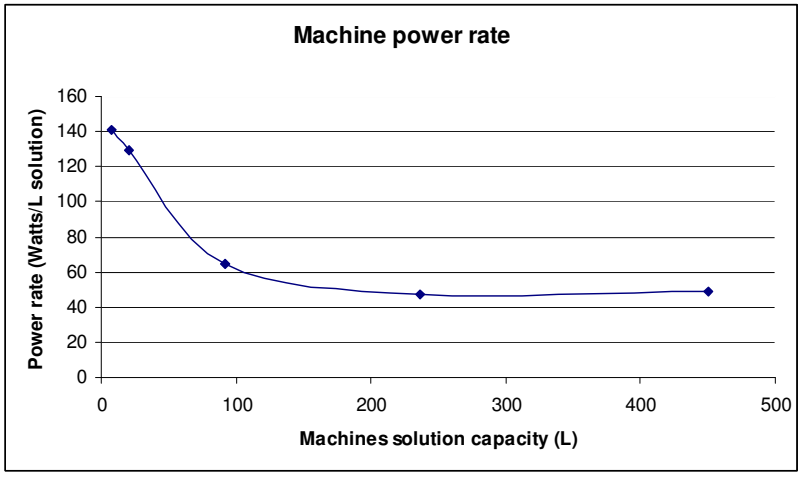


Figure 5-11 Power rate of ultrasonic machines

The previous graph shows that small capacity machines are less effective than large capacity machines. Given the fact that 1/3 of the tank volume is taken by cleaned parts, the number of parts per machine is determined in the following Table 5.14.

Table 5-14 Number of parts per machine

		Machine capacity (L)				
		8	21	92	236	450
Number of parts	Aluminum housings	N/A	N/A	3	9	18
	Steel gears	2	7	30	78	150
Solution volume (L)		6	14	62	158	300

Cleaning time evolve between 5 to 30 minutes depending on parts geometry, additives and dirt level. An average time of 15 minutes will be assumed for the calculation of ultrasonic cleaning energy given Table 5.15.

Table 5-15 Ultrasonic cleaning energy consumption

		Machine capacity (L)				
		8	21	92	236	450
Energy per part (kWh/part)	Energy per aluminum housing (Wh/part)	N/A	N/A	333.5	208.5	205.5
	Energy per steel gear (Wh/part)	94	64	33.5	24	24.5
Volume energy (kWh/ton)	Energy per ton aluminum (Wh/ton sal. Alu)	N/A	N/A	81374	50874	50142
	Energy per ton steel (Wh/ton sal. Alu)	15040	10240	5360	3840	3920

The production size can be divided in three parts: the small, medium and large production. The small production is assumed to make use of 0 to 200 L tanks capacities. The medium production makes use of 200 to 600 L tanks and all larger tanks are used for massive productions. Given the high energy consumption of small productions and the dramatic and fast drop of energy consumption as production increases (figure 5.10), small production will be excluded from the calculation. Therefore, in this study, the consumptions of 208.5 Wh/Aluminum part and 205.5 Wh/Aluminum part will be considered respectively for 236 L and 450 L machines. These results will be approximated to 200 Wh/Aluminum part which is equivalent to **49 kWh/ton salable aluminum**. With the same considerations, steel gears cleaning energy consumption is between 24 Wh/steel gear for 236 L machines and 24.5 Wh/steel gear for 450 L

machines. These values can be approximated to 24 Wh/steel gear which results in **3.8 kWh/ton salable steel.**

CO_2 blasting

CO_2 or dry ice blasting is a process used for diverse applications (Table 9) that uses CO_2 pellets. The output pressures of these pellets can rise up to 450 psi (3.1 Mpa) in industrial applications. Liquid CO_2 hold in a tank is expanded in a chamber where the temperature drops from -37 C to – 78C. This transformation is performed by a "dry ice pelletizer", which power has been estimated thanks to industrial commercials at 15 HP (11 kW) for a production rate of 150 lbs/hr to 300 lbs/hr(RSG-technologies 2007) (ASCO carbon dioxide LTD 2007). The dry ice pellets are then compressed to high pressures that depend on the machine and the application. Some machines outcome pressure and power, sold by different retailers are determined Table 5.16.

Table 5-16 Blasting machines characteristics (RSG-technologies 2007) (SEMATECH 1997) (Industrial process solutions 2007)

Blasting system	Blasting pressure	Power	Dry ice consumption
RSG Ice sonic Is-35	45 to 145	30 HP	55 to 165 lbs/hr
RSG Ice sonic Is-35 H	45 to 230	50 HP	56 to 165 lbs/hr
Atlas copco air compressors SF	45 to 145	20 HP (Max)	
Atlas copco air compressors GA/GR	60 to 290	10 HP to 250 HP (Max)	Adaptable

The powers of compressors are between 10 and 250 HP. The highest powered machines are most of the time, with control systems and adaptable pressure. The ice debit is ranged between 55 lb/hr to 350 lb/hr (RSG-technologies 2007) (SEMATECH 1997) (Industrial process solutions 2007). This study will consider a machine with a moderate technology. This study will consider a compressor of 50 HP and a dry ice consumption of 100 lbs/hr. The cleaning rate depends a lot about the dirt and the material of the part. The cleaning

speeds are ranged between 0.1 ft^2 /min or 90 cm^2/ min (paint removal) to 1.5 ft^2 / min or 1400 cm^2/min. Some chemical additives can make the process even more efficient with a removal rate rising up to 3ft^2/min or 2700 cm^2/min (Gibson parts & equipments 2007) (EPA 1994). The assumptions about CO_2 blasting are summarized Table 5.17.

Table 5-17 CO2 machine assumptions

Blasting system composition	Cleaning power	Dry ice consumption	Removal rate Tr
Pelletizer	15 HP	150 lbs/hr to 300 lbs/hr	
Compressor	50 HP	56 to 165 lbs/hr	
Blaster	2 HP	70 to 220 lbs/hr	
Total	67 HP		1 ft2/min

Given Equation 5.13 and 5.14, Table 5.18 gives the time and the resulting energy consumption of aluminum and steel cleaning.

Equation 5.9 CO_2 blasting time for aluminum and steel parts cleaning

$$T_{alu\ co2} = Tr \times S_{alu\ cl} \quad [5.13]$$

$$T_{steel\ co2} = Tr \times S_{steel\ cl} \quad [5.14]$$

Table 5-18 CO_2 blasting energy consumption

	Cleaning time (hr)	Energy consumption per part (kWh/part)	Energy consumption per ton (kWh/ton)
aluminum transfer case housing	0.028	1.4	341.6
Steel gear	0.013	0.625	100

Water cleaning sprays

Another cleaning process is the solution spray. There exist various sizes and power of these spray wash machines. In order to determine the washing energy consumption, two spray machines retailers' catalogues have been used. Table 5.19 and Table 5.20 determine the machine characteristics of two companies (Uniwashers 2007) (LS industries 2007). The solution capacity is the volume occupied by the cleaner; the loading capacity is the maximum load of the machine. The heating power can be use for the wash phase but also for the rinsing and the drying phase. The pump power is dedicated to spray the part. Wash, rinse and dry phases make use of these sprays as well.

Table 5-19 Water cleaning machines specifications (LS industries 2007)

Equipment	Solution Capacity	Loading capacity	chamber capacity	Heating power	Pump power	Output pressure
LSW-5000 rotary washer	80 gallon		0.5 m3	9 kW	7.5 HP	
36 RWB Jet spray washer	180 gallon	1000 lbs	0.5 m3		10 HP	
55 RWB Jet spray washer	200 gallon		1.3 m3		15 HP	
72 RWB Jet spray washer	700 gallon		5.3 m3		20 HP	

Table 5-20 water cleaning machines specifications (Uniwashers 2007)

Equipment	Loading capacity	Solution capacity	Chamber m3/ belt m2 capacity	Heating power	Pump motor	Blower	Output pressure
WC	500lbs	30 gallons	0.2 m3	6 kW	1 HP		75 PSI
	1000 lbs	50 gallons	0.5 m3				
Premium Industrial Top Load Model TL	1500 lbs	170 gallons	0.6 m3	18 kW	5 HP		50 PSI
	2000 lbs	530 gallons	2.4m3	36 kW	15 HP		80 PSI
Modular conveyor cleaning system MCCS	1000 lbs	200 gallons	2 m x 1.4 m	36 kW (Wash) 18 kW (Rinse) 36 kW (Dry)	5 HP	10 HP	60 PSI

The heating power and pump power resulting from the previous catalogue research are summarized Table 5.20 and Figure 5.11. Heating power is determined in kW while pump power is given in HP. The wash cycle is 0 to 60 minutes long, depending on the dirt, the geometrical complexity of the part, composition of the cleaning solution, etc.

Table 5-21 Water spray cleaning power specification

	Volume wash (m3)				
	0.2	0.3	0.6	2.5	5.3
Heating power (kW)	6	9	18	36	
Pump power (HP)	1	3	10	15	20
Total (kW)	6.75	11.24	25.4	47.2	

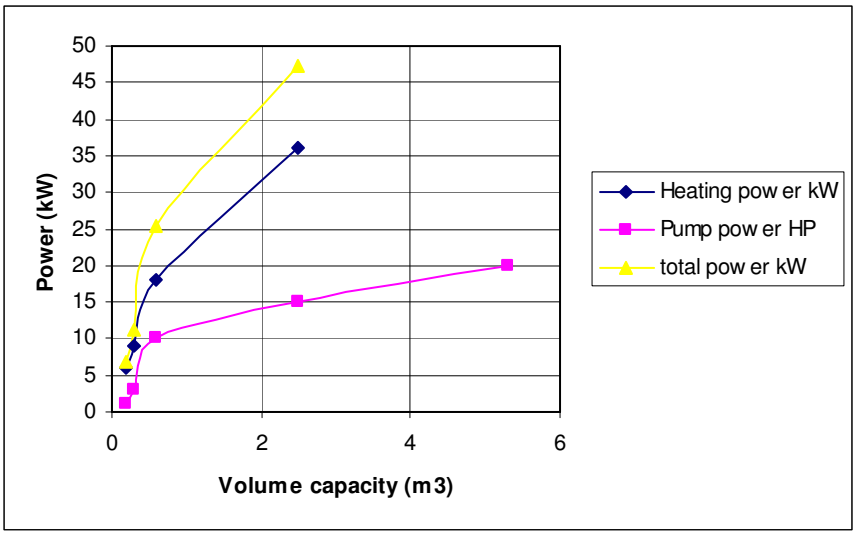


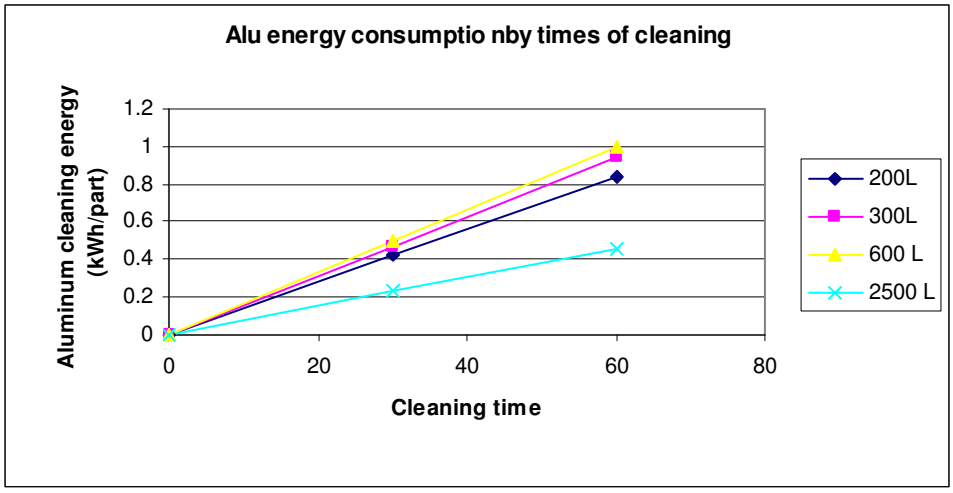
Figure 5-12 heating and spray washing power

In order to determine the energy consumption of washing, it is necessary to apply the cleaning process to the two case studies. As determined in Figure 5.12, the heating power

in function of the capacity is approximated to a linear curve. The ratio between volume occupied by parts and tank volume is $\frac{1}{3}$. The envelop volume is considered here for calculation. The energy used per part depends on the cycle length. The time depends on the volume but also on the cleaners and the level and type of dirt. Table 5.21 gives the number of parts in function of the volume capacity of the washing machine used and also the energy per part depending on the cycle time.

Table 5-22 Water cleaning spray energy consumption

	Part volume (L)	Machine chamber (L)	Number of parts	Total power machine (kW)	Energy /part Time cycle 30 min (kWh)	Energy /part Time cycle 60 min (kWh)
Aluminum transfer case	8	200	8	6.75	0.42	0.84
		300	12	11.24	0.47	0.94
		600	25	25.4	0.5	1
		2500	104	47.2	0.23	0.46
		5300	221			
Steel gears	1	200	66	6.75	0.051	0.102
		300	100	11.24	0.056	0.112
		600	200	25.4	0.0635	0.127
		2500	833	47.2	0.028	0.056
		5300	1766			



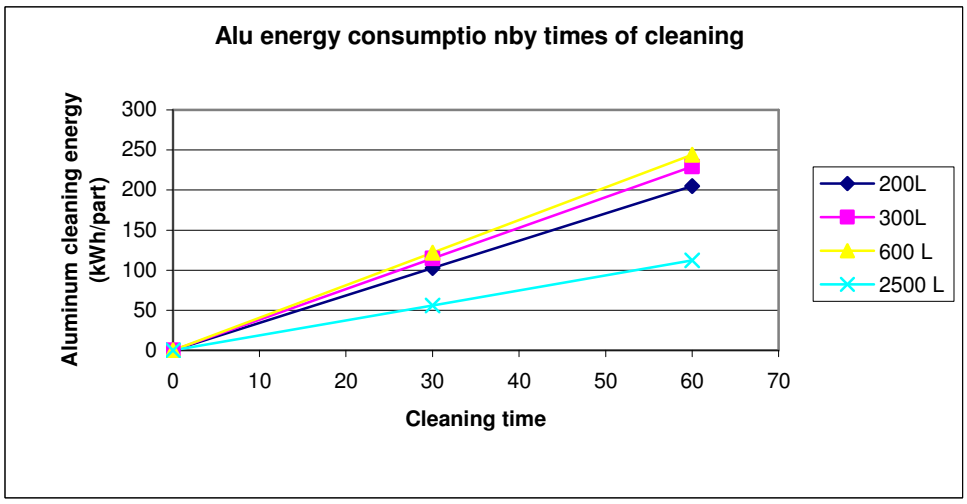
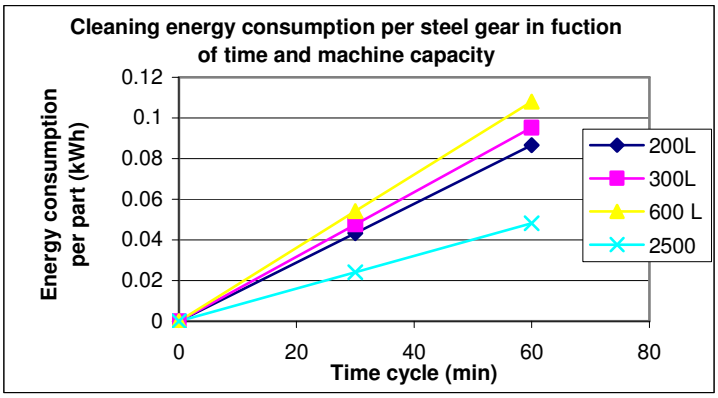


Figure 5-13 Aluminum housings cleaning energy consumption



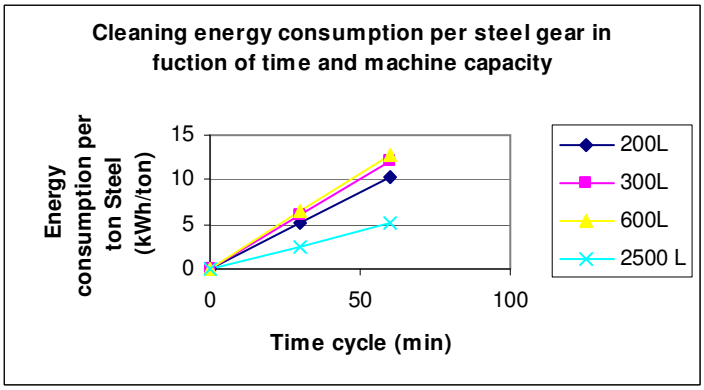


Figure 5-14 Steel gears cleaning energy consumption = f (cleaning time, machine capacity)

In order to be able to compare water spray to the other processes, a time of 15 minutes cleaning will also be assumed. The resulting energy consumptions are given Table 5.22.

Table 5-23 15 minutes water spray cleaning energy consumption

		Machine chamber			
		200	300	600	2500
Energy consumption per part (kWh/part)	Aluminum transfer case (8L)	0.12	0.21	0.22	0.24
	Steel gear (1L)	0.025	0.0281	0.03	0.014
Energy consumption per ton (kWh/ton)	Aluminum transfer case (8L)	29.28	51.24	53.68	58.56
	Steel gear (1L)	4	4.5	4.8	2.2

Given Table 5.22, the average energy consumption of aluminum transfer case can be approximated at 0.2 kWh/part which results in **49 kWh/ton salable aluminum**. In the same way, steel gears energy consumption can be approximated at 0.025 kWh/part (Mean average), which is equivalent to **4 kWh/ton salable aluminum.**

Solvent vapor degreasing process

Degreasing vapor is a process using solvents such as n-Propyl Bromide (nPB, boiling temperature 80 C) and Hydrofluoroethylenes (ex: HFE 7100, boiling temperature 60C). These solvents and their use will be detailed in Chapter 7 (Section 7.3.2 Material purification). These cleaning solution are heated to their boiling point (respectively 87 C and 60 C) and evaporated in the cleaning chamber. The top of the cleaning tank is made of refrigerant coils. This top part is called the *cold trap* and stops vapor's rise by condensation on the cold coils. The dirty part is then introduced at room temperature into the tank between the cold coils and the heating chamber (Zone A). The vapor solvent condensates on the part, dissolves greases and oils and flushes them away. This is detailed in Figure 4. It is interesting to notice the boiling point is the most solvent will condensate on the part.

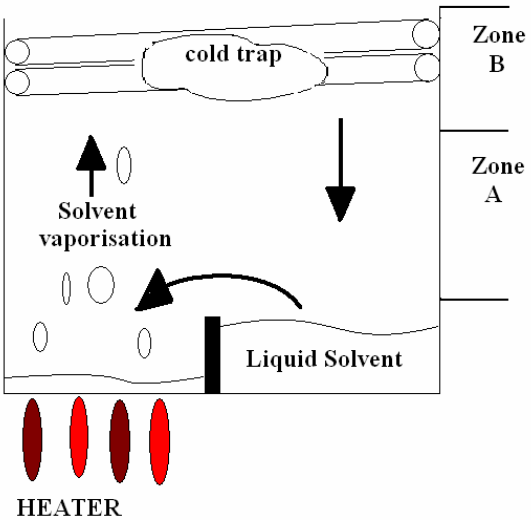


Figure 5-15 Solvent vapor degreasing machine

Vapor degreasing machine

In order to determine the energy consumption of vapor degreasing machines, machines from different capacities and different brands have been studied. The characteristics of these machines are given Table 24. The two brands are Flonitech and Baron Blakeslee.

Table 5-24 Vapor degreasers heating capacity

	Flonitech		Baron Blakeslee	
Capacity (L)	20	1000	888	450
Heating power (kW)	3	15	24	18

These heating power are represented Figure 5.17.

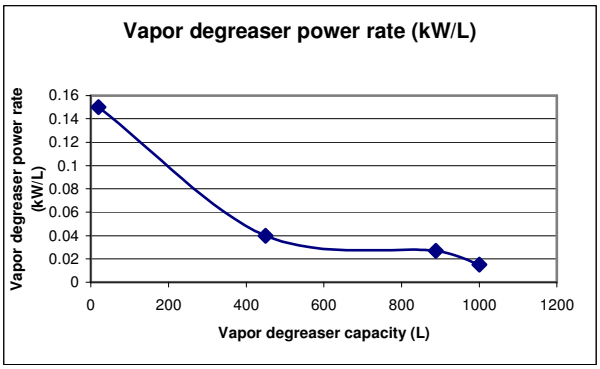


Figure 5-16 Vapor degreaser power rate (kW/L)

Figure 5.25 shows that power decreases as machine capacity increases. Therefore, giving a standard power for vapor cleaning machine would not be accurate. There fore, as previously, energy consumptions will be given in function of machine capacities. Before calculating energies, cooling power still needs to be detailed. In fact, as described previously, vapor degreasers are equipped with cooling coils that consume power as well. This consumption is determined Table 5.25.

Table 5-25 Vapor degreasers cooling power capacity

	Flonitech		Baron Blakeslee	
Capacity (L)	20	1000	888	450
Cooling power (kW)	0.25 HP	2 HP	0.75 HP	0.75 HP
Maximum capacity (kWh)		56000		

The gray zones represent absence of valuable data. The cooling capacity of Flonitech 20L and 1000L cleaner are assumed to be respectively 1 / 4 HP (0.18 kW) and 2 HP (1.5 kW). The total energy consumption (kWh) and energy rate (kWh/L) of each machine resulting from heating and cooling is given Table 5.26. The time of one cleaning cycle is assumed to be 15 minutes.

Table 5-26 Vapor degreasing energy consumption

15 minutes cleaning	Flonitech		Baron Blakeslee	
Capacity (L)	20	1000	450	888
Total power (kW)	3.186	16.5	18.56	24.56
Energy consumption (kWh)	0.8	4.125	4.64	6.14
Energy consumption rate (kWh/L)	0.04	0.004	0.01	0.007

Figure 5.15 represents the energy consumption rate of each vapor degreaser in function of the machines volume capacity.

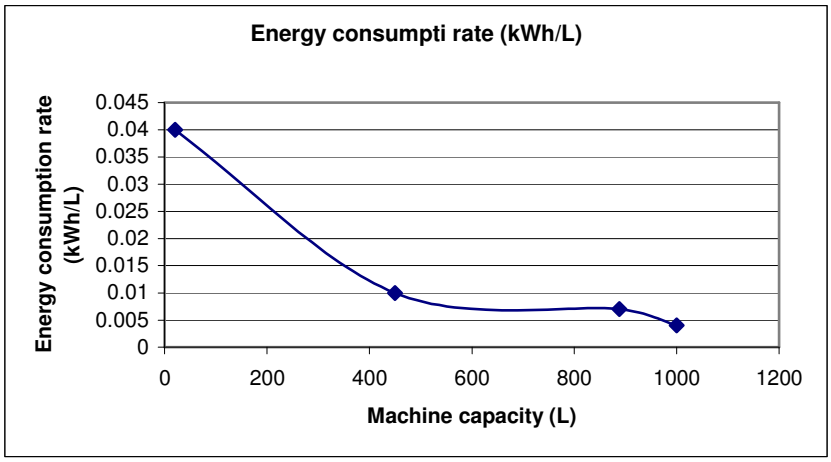


Figure 5-17 Vapor degreasing energy consumption rate (kWh/L)

The production size can be divided in three parts: the small, medium and large production. The small production is assumed to make use of 0 to 200 L tanks capacities. The medium production makes use of 200 to 600 L tanks and all larger tanks will be used for massive productions. Given the high energy consumption of small productions and the dramatic and fast drop of energy consumption as production increases, small production will be excluded from the calculation. Therefore, considering cleaning processes using 200 L to 1000 L tanks, 0.01 kWh/L will be considered as a valuable approximation of vapor cleaning energy consumption rate. The ratio parts/ tank capacity is assumed to be $\frac{1}{3}$. Table 5.26 gives the energy consumption resulting from the aluminum transfer case housing and the steel gears vapor cleaning.

Table 5-27 Vapor cleaning energy consumption

		Capacity (L)			
		20	450	888	1000
Energy consumption (kWh)		0.8	4.64	6.14	4.125
Number of parts	Aluminum housing (8L)	NA	18	37	41
	Steel gears (1 L)	6	150	296	333
Energy consumption per part (kWh/part)	Aluminum housing (8L)	NA	0.26	0.16	0.1
	Steel gears (1 L)	0.13	0.03	0.02	0.01
Volume energy consumption (kWh/ton)	Aluminum housing (8L)	NA	63.44	39.04	24.4
	Steel gears (1 L)	20.8	4.8	3.2	1.6

Considering medium to large productions and given Table 5.26, the energy consumption can be approximated to 0.18 kWh/aluminum housing or **40 kWh/ton salable aluminum** and 0.02 kWh/steel gear or **3.2 kWh/ton salable steel**.

Table 5.27 summarizes the energy consumption of the different cleaning processes studied in this chapter.

Table 5-28 Cleaning energy consumption summary

		Energy consumption	
		kWh/part	kWh/ton
Ultrasonic	Aluminum	0.2	49
	Steel	0.024	3.8
CO2 Blasting	Aluminum	1.4	341
	Steel	0.625	100
Spray washing	Aluminum	0.2	49
	Steel	0.025	4
Vapor degreasing	Aluminum	0.18	40
	Steel	0.02	3.2

Table 5.27 shows that energy consumptions are between 25 and 50 kWh/ton for aluminum and 3 to 4 kWh/ton for steel cleaning except for CO_2 blasting processes where the consumption of energy are very high. Given the fact that CO_2 blasting is a new method, very expensive and used in case of precise works, the study will not use the results of this particular method in the evaluation of cleaning processes. Nevertheless, the CO_2 study was important to see the diversity of cleaning and the disparity between energy consumptions.

Consequently, the energy consumption for cleaning process is evaluated as the mean average of Ultrasonic, water spray blasting and vapor degreasing machines energy consumption. This results in 37.8 kWh/ton salable aluminum and in 3.7 kWh/ton salable steel cleaning energy consumptions.

5.3 Phase3: Material's properties modification

5.3.1 DS phase 3, energy consumption analysis

In this study, material's properties modification is assumed to be absent from the disposal strategies. This is rarely the case in the industry. In fact, in general, aluminum parts manufacturers and aluminum producers are different businesses. Therefore, aluminum is processed in a plant, rolled into aluminum roles and distributed to the parts manufacturers who melt the aluminum and cast it into a usable part. This scenario implying a supplementary melting-casting is not considered in this study. This has been done to study the best case of disposal against the worse case of remanufacturing. This has been done to give a minimal gap between the strategies and to verify that remanufacturing strategies were not studied with a subjective advantage. The study is impartial and will give the minimum advantage that remanufacturing has compared to disposal. The material's properties modification phase is **0** ***kWh/ton salable aluminum*** energy consuming for aluminum disposal strategies.

5.3.2 RCS phase 3, energy consumption analysis

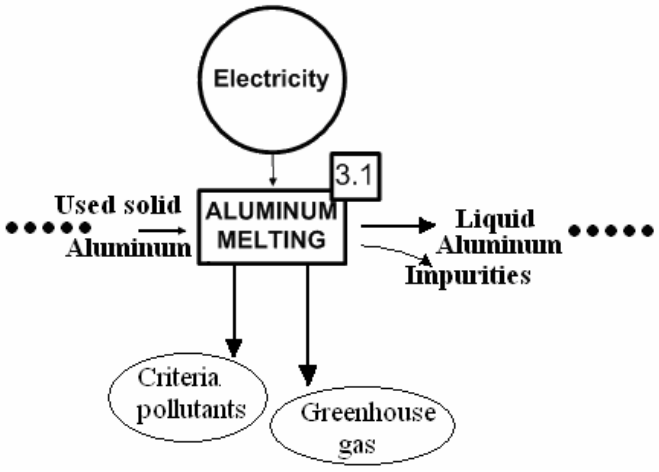


Figure 5-18 Aluminum transfer case RCS Phase 3 process analysis

5.3.2.1 Aluminum RCS process 3.1: Aluminum melting

Once aluminum has been sorted and identified as recyclable, the scrap is molten and then sent to casting. Between these two processes, liquid aluminum is kept at high temperature in a holding mold. These three steps energy consumption will be studied in the section. There exist different types of furnaces used to melt aluminum. Gas crucible, gas reverberatory, electrical reverberatory and electrical induction are widely used in the industry. Table 5.28 gives a first approach of furnaces energy consumption by giving their efficiency. (BCS November 2005).

Table 5-29 Melting furnaces capacities, melt loss and efficiency (DOE/CMC)

Aluminum	Melting Furnace	Thermal efficiency
Electrical	Induction	59-76 %
	Electric Reverberatory	59-76%
Gas	Crucible (Gas)	7-19%
	Reverberatory (Gas)	30-45%
	stack Melter (Gas)	40-45%

Furnaces used to melt aluminum are electric, gas reverberatory and gas crucibles. Attention will be focused on these three machines. Reverberatory furnaces are constructed with aluminum-resistant refractory lining and a steel shell. Figure 5.17 gives an idea of gas reverberatory furnaces functionality and shape. Crucibles are the oldest furnaces used to melt metals. As shown Figure 5.17, they have a simple architecture that results in a low maintenance cost.

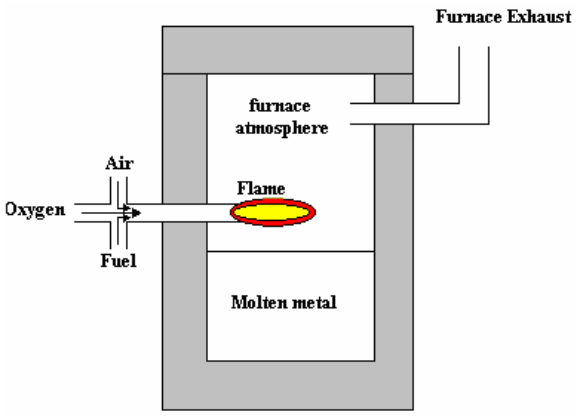


Figure 5-19 Reverberatory furnace

Table 5.28 shows that electrical furnaces are more energy efficient on-site than gas furnaces (The Ohio State University 2000-2003). Nevertheless, electricity is 3 times more expensive than gas and justifies the fact that, in the melting industry, gas is much more used than electricity. (The Ohio State University 2000-2003)

Given the multiple and sometimes disputable results found in the literature concerning aluminum melting, two approaches will be used to define the effective energy melting energy consumption. The first approach is the calculation of the energy necessary to melt one ton of aluminum using thermodynamics laws and furnaces efficiencies given Table 5.28. The second approach will use data found in the literature. Governmental and academic surveys and results will be exposed and compared to the data issued by the calculation performed below. In this study, preheating and metal preparation (ex: drying) are not considered. These processes are dependent on many uncertain parameters such as work and security policies. They are not considered in this study. The first law of thermodynamics gives:

$$Q = m_{Alu}\, Cp_{solid}\ \Delta T + m_{Alu}\, Cp_{liquid}\ \Delta T + m_{Alu}\ \Delta Hf \qquad [5.15]$$

The aluminum properties necessary to utilize the first law of thermodynamics are given below (Rundman):

$m_{Alu} = 1000$ kg

$Cp_{solid} = 917$ J kg^{-1} C^{-1}

$Cp_{liquid} = 1080$ J kg^{-1} C^{-1}

$\Delta Hf = 395995$ J kg^{-1}

$Q_{1ton} = 1000 \times 917 \times (660 - 20) + 1000 \times 1080 \times (700\text{-}660) + 1000 \times 395995 = 1026075000$ J

$Q_{1ton} = 1026075000$ J= 285 kWh

The calculation shows that the energy consumption of 1 ton aluminum melting is Q= 285 kWh/ton. Table 5.29 gives the energy resulting form the previous equations considering furnaces efficiencies determined Table 5.28.

Table 5-30 Energy consumption by furnaces resulting from calculation

Power	Furnaces types	Energy [kWh/ton]			Energy [Millions BTU/ton]		
		Best case	worse case	Average	Best case	Worse case	Average
Electric	Reverberatory	375	483	429	3.9	4.9	4.4
Gas	Reverberatory	630	950	790	2.7	3.2	2.1
	Crucible	1500	4070	2800	5.1	13.9	5.1

The second approach focuses on governmental data surveying effective industrial applications. The energy consumption estimation of electrical reverberatory, gas reverberatory and crucible's defined by governmental surveys and studies are reported Table 5.30.

Table 5-31 Energy consumption resulting from governmental sources ((Energetic Inc 1997) (Eppich 2004))

Power	Furnaces types	Energy [kWh/ton]			Energy [Millions BTU/ton]		
		Best Case	Worse case	Average	Best case	Worse case	Average
Electric	Reverberatory	190	260	225	0.6	0.8	0.7
Gas	Reverberatory	820	1640	1230	2.5	5	3.8
	Crucible	820	2290	1555	2.5	7	4.75

Thermodynamic calculations have been performed for an ideal case and therefore are not exactly transferable to effective processes. Nevertheless, these results give a good approximation and support to judge the data found in the literature. The results issued by the two different methods are coherent. The governmental data will be used in the energy consumption estimation. The average energies given Table 5.30 for gas furnaces are 4.3 Millions BTU +/- 0.5 MBTU. This result is coherent with the average energies calculated in table 5.29. Therefore, the energy consumption of melting Aluminum by gas is estimated at 4.3 Millions BTU/short ton or **1400 *kWh/ metric ton salable aluminum.***

5.3.2.2 Aluminum RCS process 3.1.1 (optional): aluminum holding

As in the previous part, the holding furnaces will be studied through calculation and literature. The calculation will use heat transfer laws to define the energy delivered to 1 ton of metal to keep it at a temperature of 700 C [above melting point] in an ambient temperature of 20C. Conduction principles are used here to determine how much energy is lost through liquid aluminum and through the walls (Figure 5.19). The conduction is assumed to be the dominant heat transfer occurring compared to convection and radiation. Ceramic insulation is widely used in furnaces walls insulation. Many types of ceramics exist. A ceramic made of 80% of Al_2O_3 and 20% of SiO_2 has been considered in the heat transfer calculation. Its maximum operating temperature is 3090 F and its

thermal conductivity is 0.31 W m^{-1} K^{-1}. The holding furnace is assumed to be cylindrical. The total surface in contact with the melt metal is a 1.3 m high and 1.15 m radius cylinder, two 1.15 m radius disks on top and bottom. The properties of the furnace are summarized Table 5.31.

Table 5-32 Holding furnaces properties

Holding furnace	
maximum capacity	15 tons
Depth	1.3 m
Radius	1.15 m
Volume	5.5 m3
Wall surface	18.5 m2
Wall thickness	0.25 m
Insulating ceramic	80% AlsO3 20% SiO2
Maximum Use temperature	1700 C
Thermal conductivity at 800 C (1500 F)	0.31 W/m C
Furnace intern temperature	700
Ambient temperature	20

The energy lost by conduction through insulating ceramic walls is given by Boltzman conduction formula (Equation 5.16) and illustrated Figure 5.19:

$$Q = \frac{T_1 - T_4}{(\sum_i \frac{\Delta ri}{kiAi})} \qquad [5.16]$$

k= wall thermal conductivity

A= Wall area

Δ_r *= Wall thickness*

$$Q = \frac{(700-20)\times 18.5}{(\frac{1.15}{221}+\frac{0.25}{0.31})} = 10230W = 10.23\ kW$$

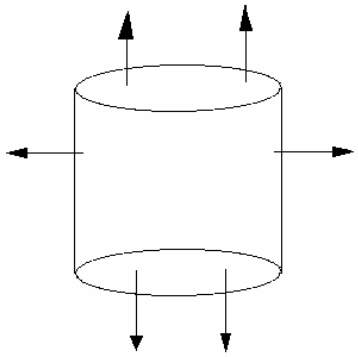


Figure 5-20 Energy lost by conduction

The minimum power required for a holding furnace appears, thanks to the previous conduction calculation to be 10 kW. The literature research following will help to verify this result and to determine working furnaces actual consumption. The holding furnaces energy consumption have been inspired by an operational casting plant study for the U.S department of energy and commercialized furnaces specifications (Jerald Brevick and The Ohio State University 2000-2003), (Thermal products solutions 2007). Most holding furnaces commercialized have a maximum capacity of 100,000 lb [45 tons]. As for melting machines, there exist different holding machines. Some of them are powered with electricity while other are powered with gas. These machines are defined Table 3, they work 24 hours a day, 7 days a week and 365 days a year. Nevertheless, it is important to underline that the machines do not have linear consumptions. In fact, in the case of holding furnaces, there is a significant difference during production compared to off-production. During production, the frequent openings of the doors result in high loss of heat and therefore loss of power. The consumption can exceed 50% the off-production usual consumption (The Ohio State University 2000-2003). In order to get a realistic approach of the energy consumption in such conditions, the overall average energy uses

are considered here. They gather the "off-production" and "During production" phases. Table 4 gives the energy of two holding furnaces found on public sales (Golden pond metal die-casting co.ltd 2007). It details the energy consumption and the capacity of an electrical holding furnace and a gas holding furnace. The results of the gas holding furnaces correspond to the worse case of consumption of two holding furnaces, the 62-GH-2600 (2600 lbs max capacity) and the 62-GH-5500 (5500 lbs capacity) (TPS 2006). Their specifications are reported Table 5.32 and Table 5.33.

Table 5-33 holding furnaces specification

Furnace type	Appx hold cap (lbs)	Appx hold capacity (tons)	Max input (BTU)	Max input (kWh)	Energy consumption (BTU/lb)	Energy consumption (kWh/ton)
62-GH-2600	2600	1.18	333 000	98	128	83
62-GH-5500	5500	2.5	482 500	141	88	56

Table 5-34 Holding furnaces capacity and energy consumption

Holding furnace	Type of Power	Energy	Capacity
Golden pond furnaces series	Electrical	6 [kWh/ton]	0.5 tons
MPH Aluminum Reverberatory holding furnaces	Gas	10 [kWh/ton]	1.5 tons to 45 tons

The global energy consumption of molten metal holding remains around **10 kWh/ton** aluminum. This value will be considered as representative of electrical and gas heat generation. Holding furnaces hold molten aluminum for the following casting step. During casting, aluminum is transferred from the holding furnace to the casting mold. This transfer might be automatic or manual (Ex: ladling). Some casting machines have a

holding furnace integrated. Nevertheless, for the clarity of the energy evaluation, melting, holding and casting machines will be considered as independent entities, with negligible loss of energy during material transfers. The casting machine used for this evaluation is a die-casting machine. It will be studied in the following section.

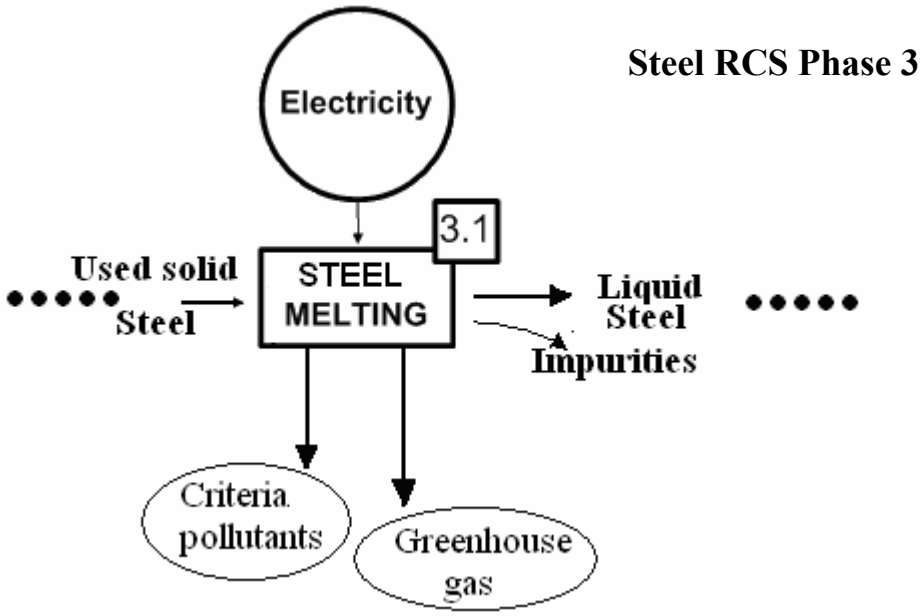


Figure 5-21 Steel gear RCS and RMS phase 3, process analysis

5.3.2.3 Steel RCS process 3.1: scrap steel melting

As mentioned before, used steel can be molten in two furnaces that are basic oxygen furnaces (BOF) and electrical arc furnaces (EAF). In the first unit, only a part of the steel is scrap, as in the second unit, the primary material is 100% scrap. This is why the EAF will be the object of this used steel melting section. The energy input is 60% electricity that goes through three electrodes and creates an arc capable of melting the

scrap. The rest of the energy is mainly brought by chemical reaction with the oxygen, lime natural gas and graphite added in the furnace (CMP The EPRI Center for materials Production 1997) (Jones 2005). The typical global energy consumption of the furnace varies between 400 kWh/metric ton molten steel and 770 kWh/ton molten steel depending on the data sources (Stubbles 2000) (CMP The EPRI Center for materials Production 1997) (Energetics Inc. for US Department of Energy 2000). 700 kWh/ton steel molten will be used in this study. Usually, the electrical energy consumption is evaluated around 450 kWh/ton. This result does not consider the initial assumption of 60% electricity input but appears in most of the sources. Therefore, a global energy consumption of **700 kWh/ton steel** will be used where **450 kWh/ton steel** are generated by electricity and the rest by oxygen, natural gas, electrode consumption and other additives (Stubbles 2000) (Energetics Inc. for US Department of Energy 2000). These data do not consider auxiliary treatments such as electrodes making or oxygen producing. These processes are out of the study's boundaries. However for information, electrode production consumes around 5000 kWh/ton graphite. Given the consumption of 4.5 lbs electrode/ ton steel (best practices), the related energy consumption is not negligible and is omitted here only in respect to the study's primary assumptions.

5.3.3 RMS phase 3, energy consumption analysis

Steel and aluminum remanufacturing phase 3 is empty. In fact, in these scenarios, there is no change in the function of the parts.

5.4 DS and RCS phase 4: Definition of material's final property and functionality

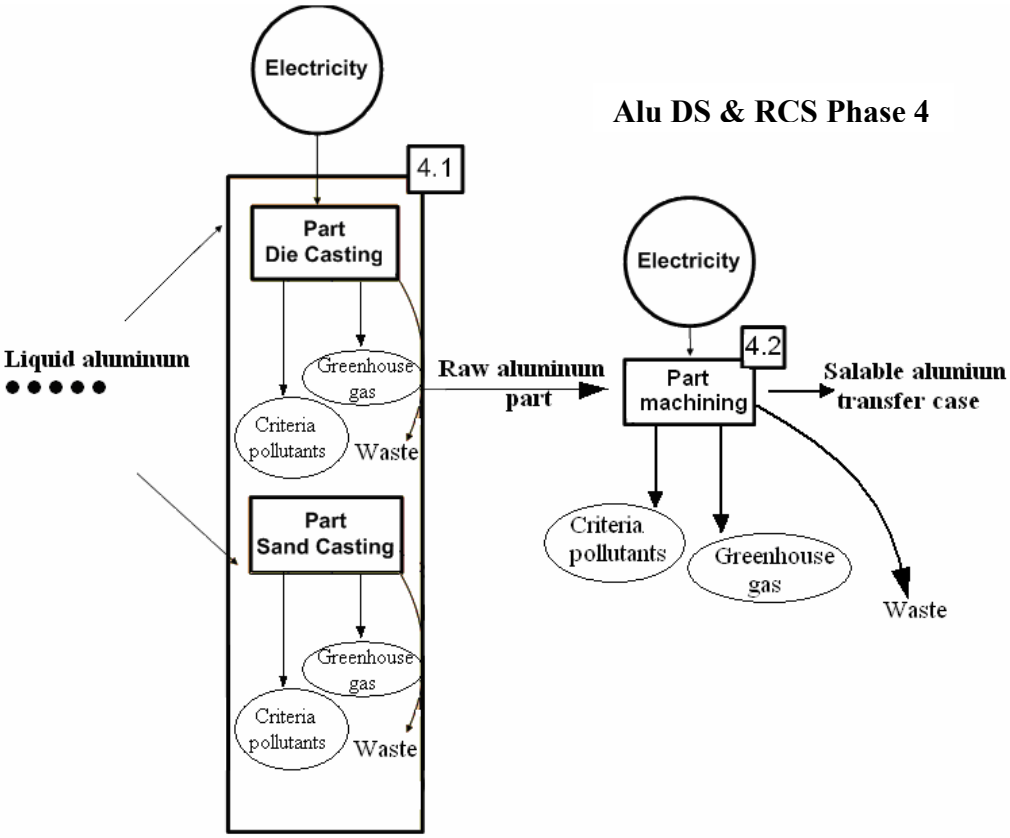


Figure 5.20 Aluminum DS and RCS Phase 4, process analysis

5.4.1 DS and RCS, phase 4, energy consumption analysis

5.4.1.1 Aluminum DS and RCS process 4.1: Aluminum casting

Die casting

Contrary to non-permanent casting methods such as Sand-casting and Lost-wax casting, Die-casting is realized with no systematic destruction of the mold. This allows high

productivity that can increase up to 400 injections per hour depending on the mold design (EPA Office of Compliance Sector Notebook Project 1998). Die casting is widely used for aluminum but not for high melting point such as steel. Therefore, another casting process, the sand-casting also widely used in the industry and applicable to both metals will be studied further. There are two different ways of die-casting. Depending on the melting temperature of the material, this process might be realized with a cold chamber or a hot chamber. In fact, in the hot chamber case, an important part of the casting system is immerged in the molten metal. No refills are needed between each casting. This is why this particular process allows rapid cycles and high productivity. Nevertheless, in order to avoid degradation of the installation that is immersed in the molten metal, only low melting points material such as lead or zinc alloys can be used. Whereas in the cold chamber system where no significant parts are in permanent contact with the melt metal, higher melting points materials, such as aluminum can be used. This is why, in this study focusing on an aluminum transfer case housing, cold chamber machines will be studied . The mold metal is transferred for each part casting via a ladle. The energy consuming phases of the die-casting process are injection, pressure maintenance during solidification and ejection. The injection phase is 0.01 to 0.04 sec long**.** The energy involved in the injection phase depends on the design of the inlet pipe. Nevertheless, given the short time necessary to inject the molten metal in the cast mold, the energy corresponding will be neglected in the calculation. The energy consumed by the mechanical pressure hold by the dies walls, are going to be evaluated in this section.

The cycle's times and therefore the energy consumption, depend on the part design and on the die-design that determines the number of parts produced per injection. Therefore,

for the energy consumption calculation, the worse case from efficiency point of view will be assumed, that is 1 part cast per injection. The die is supposed to be made of steel.

In order to define the casting resulting energy consumption, it is first necessary to estimate the time of a cycle. The solidification time in a die-casting mold can be estimated thanks to the following relations (Rundman 2006):

$$ts = \frac{\rho_{metal}[\Delta H_F + C_{Metal}(T_p - T_m)]}{h(T_m - T_0)}(\frac{V_{Metal}}{A_{Metal}}) \qquad [5.17]$$

ρ_{metal} = Metal density (kg/m^3)

ΔH_f = Latent heat (J/kg)

C_{metal} = Specific heat (J/kg K)

T_p = Metal temperature(C) T_m = Melting temperature (C)

h = Heat transfer coefficient through combination of two materials (W/m^2 C)

T_o = Solid metal temperature (C)

V_{metal} = Volume cast part (m^3)

A_{metal} = Contact area with die walls (m^2)

$\rho_{aluminum}$ = 2700 kg/m^3

$\Delta H_{fAluminum}$ = 395995 J/kg

$C_{Aluminum}liquid$ = 1080 J/ kg C

T_p = 700 C

T_m = 660 C

$h_{Aluminum-steel}$ = 2300 BTU/hr ft^2 F = 2300×5.647 = 13058 J/sec m^2 C

$T_o = 150$ C

$$\text{V Metal} = \frac{Wpart}{\rho_{alu\,\min um}} = \frac{4.1}{2700} = 0.0015 \text{ m}^3$$

$$\text{Apart} = 2 \times \pi \times (\frac{D^2{}_1}{4} - \frac{d^2{}_1}{4}) + 2\pi \frac{D_1}{2} \times L + 2\pi \frac{d_1}{2} \times L = 0.25 m^2$$

$$ts = \frac{2700[395995 + 1080(700 - 660)]}{13058(660 - 150)} (\frac{0.0015}{0.25}) = 0.95 \text{ sec}$$

Considering the engine power of a cold chamber machine at 20 kW (LK Machinery INC. 2007), the resulting energy consumption of die-casting is 0.005 kWh/part. This is equivalent to 1.3 kWh/ton salable aluminum (considering an optimum machine efficiency of 100%). Die casting electrical motor power found in governmental reports and surveys are between 22kW (30HP) and 37 kW (50 HP) and up to 50 kW (Energetics Inc. for US Department of Energy 1999) (Eppich 2004). Governmental sources also confirm the fact that dies can cycles times range from less than 1 second to 30 seconds. This verifies the range of mechanical energy consumption calculated before. Given the low energy consumption of mechanical pressure, it will be neglected. Nevertheless, an important source of energy consumption remains to be studied in the die-casting process. In fact, a preheating of the mold is necessary in hot chamber and in cold chamber die machines. This energy consumption is estimated by governmental sources to be 400 kWh/ton salable aluminum for hot chamber die machines and 460 kWh/ton salable aluminum for cold chamber die machine. The die machines considered here are electrically powered (Energetics Inc. for US Department of Energy 1999). The total energy consumption of die casting machines will be estimated at **430 kWh/ton salable aluminum.**

Another process widely used in the industry is the sand casting. This process is largely developed because of the good quality of the parts realized and the low cost of molds manufacturing (Dalquist 2004). However, this process has a significant environmental impact form a solid waste and pollutants emissions point of view. In fact, sand casting molds are made of green sand and are single use molds. The mold is destroyed after each use and the resulting sand and binder present in cores and sand are disposed. 790 kg/ton salable aluminum are disposed (Department of natural resources 2005). Given the predictable negative impact of sand casting, and given the best case study of recycling and disposal scenarios, the sand casting process study will be skipped here.

Steel gears scenarios have a very different casting process compared to aluminum scenarios. Figure 5.22 illustrates steel's fourth phase that is going to be discussed.

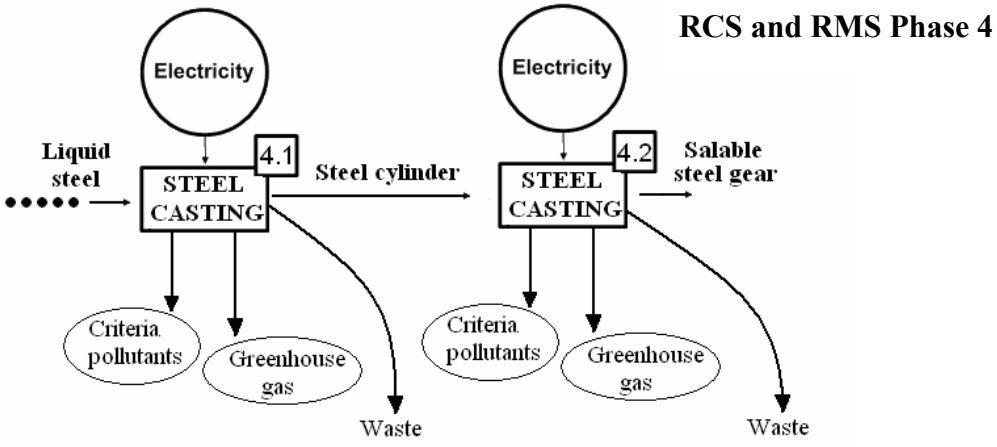


Figure 5-22 Steel gear RCS and RMS phase 4, process analysis

5.4.1.2 Steel DS and RCS process 4.1: steel casting

Approximately 96 % of the US steel production is realized with continuous cast. The rest is cast in ingot for particular shapes requirements. Ingot casting appears to be much more energy consuming than continuous casting. In fact, in the ingot casting, several phases of soaking, reheating, large amounts of scrap produced drive to an efficient process that has been successfully replaced by continuous casting, where phases such as soaking, metal reheating can be avoid for a higher metal quality result, a lower scrap loss which is responsible of a higher level of production. Continuous casting processes eventually lead to significant energy savings. Ingot casting are considered 10 times more energy consuming than continuous casting process by many valuable sources (Stubbles 2000) (Energetics Inc. for US Department of Energy 2000) (Office of Technology Assessment 1979). This explains the wide use of continuous casting compared to other steel casting processes.

Given these proportions, continuous casting will be the only process analyzed in this study. For continuous cast, molten steel is poured in into a reservoir. The molten metal is then continuously released and conveyed through rolling molds as shown Figure 5.22.

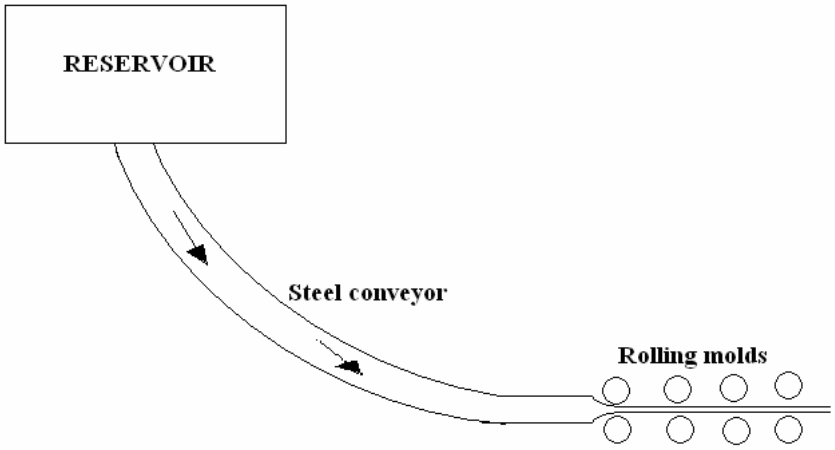


Figure 5-23 Steel continuous casting

The energy consumption of this phase has been evaluated at **150 kWh/ton salable steel** in 1994 in a industrial survey (Enerst Orlando Lawrence Berkeley National Laboratory 1999). This value is confirmed by other sources where the energy consumption is estimated around 100 kWh/ton salable aluminum. The average of **130 kWh/ton salable steel** will be used in this study for steel casting energy consumption.

Continuous casting is followed by a hot rolling phase where steel is still viscous (most of the time a re-heating phase is necessary between casting and hot rolling) (Blue Scope Steel Limited 2006). The energy consumption of this phase was evaluated around 1100 kWh/ton salable steel in 1994 (Enerst Orlando Lawrence Berkeley National Laboratory 1999). This value includes reheating phase. This energy is the same in the case of a Basic Oxygen Furnaces (BOF) use as in plants using an Electrical Arc Furnaces (EAF) melting process. Other sources give a smaller approximation of 950 kWh/ metric tons salable steel including reheating furnaces (Energetics Inc. for US Department of Energy 2000). Given these results, the energy consumption of **1000 kWh/ton salable steel** will be used in this work to quantify steel hot rolling processes.

The following step is the cold rolling. This process works on cold and therefore solidified steel. This drives to a transformation of steel's microstructure. This phase is less energy consuming than hot rolling because of the absence of heat processes. This phase's energy consumption was evaluated around 500 kWh/ton salable steel in 1994 industrial survey (Energetics Inc. for US Department of Energy 2000). This phase includes rolling and acid. This last operation helps to remove hard residues (oxides and scale) resulting from the heating processes. Pickling will be more developed in the air emissions analysis performed Chapter 7. Another source gives an energy close to 620 kWh/ton salable aluminum (Energetics Inc. for US Department of Energy 2000). **550 kWh/ton salable steel** will be used for the cold rolling phase.

To conclude, in order to prevent steel from reacting with the ambient air (Oxygen, humidity, etc…) and creating rust, but also to give the steel more hardness and resistance depending on the use, a final step or finishing is necessary. This consists in hydrogen and temperature treatments that will not be considered here given the wide range of treatment and consequential energy consumptions divergences. Table 5.34 summarizes the steel casting operations energy consumption. The total energy consumption of steel casting is evaluated at

Table 5-35 Steel casting energy consumption summary

Continuous steel Casting process	Energy consumption [kWh/ton salable steel]
Casting	130
Hot rolling	1000
Cold rolling	550
Total	**1680**

5.4.1.3 Aluminum and steel DS and RCS process 4.2: machining

In the case of steel gears, casting outputs are cylindrical parts. In the case of an aluminum transfer case, the part coming out of the cast process has already a shape close to the final transfer case. This is due to the good moldability of aluminum compared to steel much more difficult to mold. Therefore, whereas complete functionality will be determined during steel manufacturing phases, only functional surfaces refining will be performed in aluminum manufacturing processes. The following study will show if this observation has an interest for the study. Two approaches were chosen here to realistically evaluate the energy consumption of the machining process. The first uses the specifications of operating machines. The second is a calculation of the part machining energy need. Three machines specifications have been extracted from literature and used for the first energy estimations (Dahmus 2004).

Table 5-36 Machine power specifications

	Energetically worst case	Energetically best case	"medium" case
Power requirements	*Machining center*	*Manual milling machine*	Automated milling machine [1998]
Start-up operations	166 kW	0.7 kW	1.2 kW
Run time operations	6.8 kW	0 kW	1.8 kW
Material removing operations	22 kW	2.1 kW	5.8 kW
TOTAL (kW)	**194.8**	**2.8**	**8.8**

Table 5.35 organizes the machines in three categories. The worst case from a power perspective is the machine with the highest power. In this case the machining center is considered as the worst case followed by the automated milling machine. The manual milling machine has the lowest power. These three machines are used for different applications and different levels of production. The manual milling machine is used for small production as the machining center is used in high production levels. The automated machine is a good compromise that might be used in high and low productions. This machine will be taken as reference in the following. The removal rates and energy requirements of this machine are given Table 5.37. In order to drive correctly the calculations, the volume removed during manufacturing is necessary. Steel gears and aluminum transfer case removed material are given respectively Equation 5.18 and 5.19 and illustrated Figure 5.24.

Volume removed:

$$\mathrm{Al} = \frac{R}{1-R} Vfinal = \frac{0.08 \times 4.1}{0.92 \times 2.7} = 132 \text{ cm}^3 \qquad [5.18]$$

Steel $= \pi \times (r_1^2 + 0.5 \times (R_1^2 - R'^2)) \times e = \pi \times (12.5^2 + 0.5 \times (100^2 - 88.5^2)) \times 30 = 116820 mm^3$

[5.19]

$= 116 cm^3$

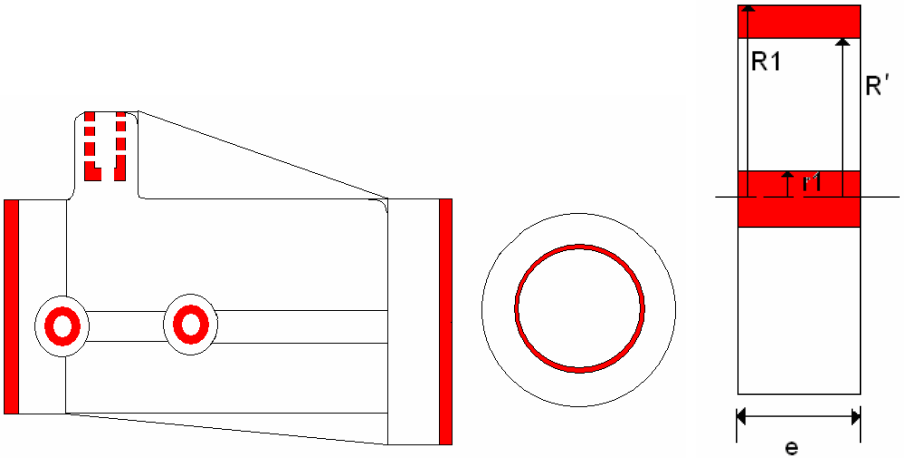


Figure 5-24 Material removed from an aluminum transfer case housing and in a steel gear

Table 5-37 Aluminum and steel machining energy consumption

	Removal rate [sec/cm3]	Energy requirement [kWh/cm3]	Volume removed [cm3]	Energy consumption [kWh/part]	**Energy consumption [kWh/ton]**
Aluminum	5	0.00064	132	0.08	**20**
Steel	1.2	0.0027	116	0.31	**50**

As Table 5.36 shows, machining energy consumption is very low compared to the other processes studied here. Therefore, this phase has no significant role from an energy perspective in the scenarios environmental impact. This will be further discussed in the final Chapter 9.

5.4.2 RMS phase 4, energy consumption analysis

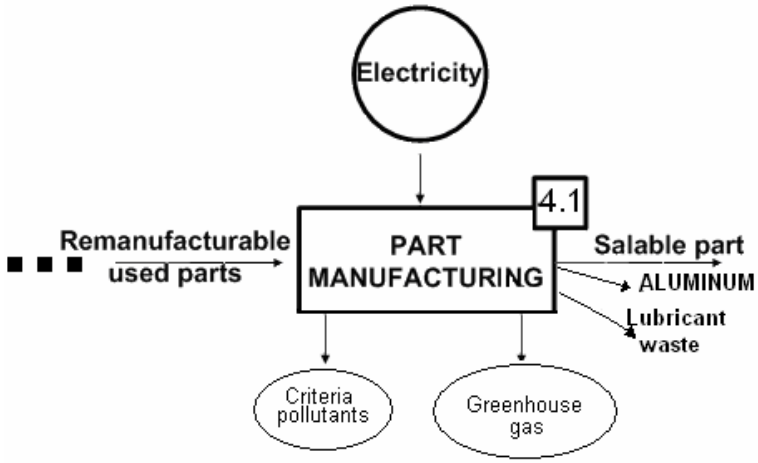


Figure 5-25 Aluminum transfer case Phase 4 processes analysis

5.4.2.1 Aluminum and steel remanufacturing process (4.1): Metal addition (Developing technology)

Metal addition is a recent technology that consists in adding material to surfaces. This technology is used in high tech industries such as aerospace. This process can also be used to add material on used parts to increase parts life time. Given the fact that this technology is applied to specific high tech domains, and because some techniques such as Laser Powder Deposition (LPD) are recent, still experimental and remain very expensive, the material addition phase will not be considered in the calculations. One technology used for metal disposing is the plasma spray. It consists in spraying particles (1 to 50 microns) on a surface. The particles sprayed are molten and accelerated by an arc (or a flame) before reaching the surface of the part. The sprayed material can be metal (Zinc, Nickel, Molybdenum, stainless steel, aluminum) but also ceramic and polymer. The temperature used in plasma sprays vary from 5000 C to 25,000 C (Flame Spray Coating

Company 2007) (Gordon England 2007). The power of some plasma sprays can be 80 kW and might rise up to 120 kW (Bay State Surface Technologies 2006). The feed rates vary between 50 and 150 g/min. The energy requirement resulting from these specifications varies between 0.014 kWh/g and 0.027 kWh/g metal deposited. (Center of the Plasma Processing of Materials 2006). In this calculation, the volume of material added is assumed to be 10 times smaller than the volume removed during the machining of a cast part given Table 5.37. Therefore, the volume of aluminum added is 13 cm^3 which is 35 g aluminum. Therefore, the energy consumption varies between 0.5 kWh/aluminum part and 0.95 kWh/aluminum part. This leads to energy consumption per ton of aluminum varying between **120 kWh/ ton aluminum and 230 kWh/ton aluminum**.

The volume of steel added is 11 cm^3 which corresponds to a steel mass of 86 g steel. The energy consumption of steel addition varies between 1.2 kWh/steel part and 2.3 kWh/steel part. This leads to energy consumption per ton of steel varying between **190 kWh/ton steel and 370 kWh/ton steel**. These energy consumptions are higher than machining processes. Nevertheless, the energy consumption of material addition remains small compared to most of the other scenarios processes summarized in Figure 5.28 and Figure 5.29.

Another technology used for metal deposing is the "Direct Laser Powder Deposition" (DLPD). Several institutions and companies have been developed this technology during this last decade. The system is similar to plasma sprays but the rate of powder deposited is less than in plasmas. The developed machines have powers varying from 500 Watts to 14 kW depending on their build rate. These build rates vary from 15 to 1000 cm^3 / hr

which corresponds to an interval of 0.04 kg/hr and 2.7 kg/hr aluminum and an interval of 0.12 kg/hr and 7.8 kg/hr for steel. However, given the modernity of these machines, they are expensive. For instance, Optomec Design Company developed a Laser system in 1997 that costs $350,000. These systems are realized at a unit scale. This is why such technologies might not be appropriate for current reuse purpose (Sears 2000).

5.4.2.2 Aluminum and steel remanufacturing process (4.1): machining

Remanufacturing scenarios use the same machining processes than in the other scenarios. Nevertheless, the quantity of material removed is inferior to the quantity removed in a new part machining. In fact, in remanufacturing scenarios, the part is already in its final shape. In recycling and disposal scenarios, the machining specifications are the same. In these machining processes, there are two phases:

- The rough machining phase
- The finish phase

The cutting power is given by equation 5.18:

$$Pc = Kc \times a \times f \times Vc \qquad [5.20]$$

Kc: Specific cut coefficient (daN/mm^2)

A: Pass depth (mm)

f: Cutting advance (mm/tr)

Vc: cutting speed (m/min)

Table 5.37 summarizes cut speeds in function of the tool and the material.

Table 5-38 Cutting speed specification

	Vc (m/min)			
	Rough		Finish	
Machined material	HSS tool	Carbure tool	HSS tool	Carbure tool
Steel	10--30	60--150	20--50	120--220
Aluminum	25--45	100--180	30--60	140--260

The motor power is given by Equation 5.21:

$$\mathrm{Pm} = \frac{Pc}{\eta} = \frac{Kc \times a \times f \times Vc}{\eta} \qquad [5.21]$$

Remanufacturing machining only finishes the part. There is no rough machining because the part was already machined in the part's previous life. Therefore, energy is mainly used for a finishing part. The specific cutting coefficient is a constant depending on the advance of the tool. This constant is determined in Table 5.38 in function of the advance f. In this case, the advance is supposed to be equal in the roughing part as in the finishing part. Table 5.38 gives the constraints on advances given the phase of machining and the tool used. It proves that advances can be chosen equal to the roughing phase, as long as the value is chosen superior to the minimal constraint.

Table 5-39 Cut speeds comparisons between roughing and finishing phases

		Vc (m/min)			
Tool	Material	Roughing ('R)	Finition(F)	1-R/F	
HSS	Steel	10	20	0.5	
		30	50	0.4	0.45
	Aluminum	25	30	0.17	
		45	60	0.25	0.21
Carbure	Steel	60	120	0.5	
		150	220	0.32	0.41
	Aluminum	100	140	0.28	
		180	260	0.31	0.3

Given Table 5.39, the speed cut augments by 40% in steel machining and by 25 % in aluminum machining. The ratio (1-R/F) is will be α in the calculations. Finally, the pass

depth a_2 in finishing phases is supposed to be $a_2 = \frac{1}{3} \times a_1$. Therefore, given all these assumptions, the power requested in recycling/disposal machining strategies is given by:

Pc Recy/diposal = P Roughing + Pc finishing = $Kc_1 \times a_1 \times f_1 \times Vc_1 + Kc_2 \times a_2 \times f_2 \times Vc_2$ [5.22]

Pc Recy/disposal =

$$Kc_1 \times a_1 \times f_1 \times Vc_1 + Kc_1 \times \frac{1}{3} a_1 \times f_1 \times (1+\alpha) Vc_1 = Kc_1 \times a_1 \times f_1 \times VC_1 \times (1+\frac{1}{3}(1+\alpha))$$

Pc recy/disposal = $Kc_1 \times a_1 \times f_1 \times VC_1 \times (1+\frac{1}{3}(1+\alpha))$

Pc Remanufacturing = Pc finishing = $\frac{1}{3}(1+\alpha)\, Kc_1 \times a_1 \times f_1 \times VC_1$

$$P_{ratio} = \frac{\text{Pc Remanufacturing}}{\text{Pc recy/dipsosal}} = \frac{\frac{1}{3}}{(1+\frac{1}{3}(1+\alpha))} \qquad [5.23]$$

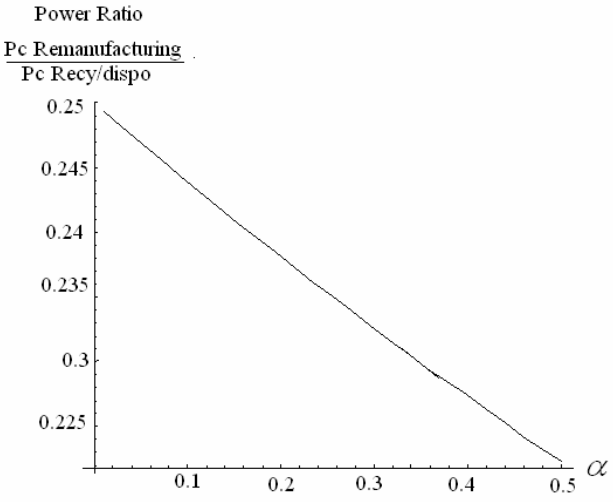


Figure 5-26 Machining power P_{ratio}

Figure 5.26 shows the linear decrease of the power ratio in function of α. Given the fact that α varies from 15 % to 45 % depending on the material machined and the tool used, the power ratio varies from 0.242 to 0.225, as demonstrated Figure 5.27.

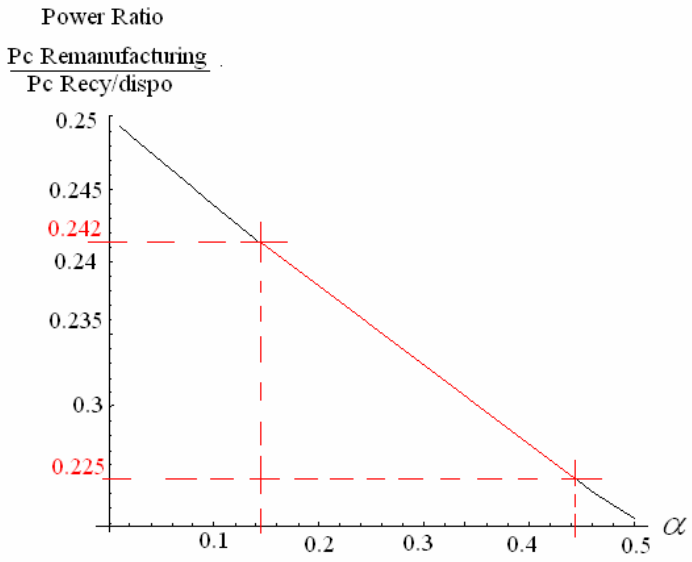


Figure 5-27 Machining Power ratio interval

$$0.225\ Pc\ Recy/disposal < Pc\ Remanufacturing < 0.242\ Pc\ Recy/disposal$$

This drives to the conclusion that the energy consumed in remanufacturing machining is approximately 5 times smaller than the machining of a new part as recycling or disposal strategies. Therefore, remanufacturing strategies machining phase is evaluated to be:

$$EN_{\text{machining remanufacturing}} = \frac{EN\ \text{machining recycling/disposal}}{5} = \frac{20}{5} = 4\text{kWh/ton}$$

[5.24]

$$EN_{\text{machining remanufacturing}} = 4\text{kWh/ton}$$

5.5 Energy consumption summary

Table 5.39 and 5.40 respectively summarizes the energy consumption of remanufacturing, recycling and disposal scenarios for an aluminum transfer case and for a steel gear. Given the fact that transportation will be studied in the next chapter (Chapter 6), phase 1: ore mining does not appear in the following tables and graphs.

Table 5-40 energy consumption of the three end-of-life strategies processes

END OF LIFE STRATEGIES	PARAMETERS	PROCESS				
		2.1	2.2	3.1	4.1	4.2
DISPOSAL STRATEGY	PROCESS	Alumina refining	Electrolysis	XXX	Transfer case casting	Transfer case machining
	TYPE OF FUEL	30 % Gas+ 40 % coal + 30 % heavy oil	Electricity	N/A	Electricity	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	14000	15000	0	430	20
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	50400	54000	0	1548	72
RECYCLING STRATEGY	PROCESS	Sorting	XXX	Ingot melting	Transfer case casting	Transfer case machining
	TYPE OF FUEL	Electricity	N/A	Gas	Electricity	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	2555	0	1400	430	20
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	9198	0	5040	1548	72
REMAN. STRATEGY	PROCESS	Sorting	Cleaning	XXX	XXX	case remachining
	TYPE OF FUEL	Electricity	Electricity	N/A	N/A	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	2555	38	0	0	4
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	9198	136.8	0	0	14.4

Table 5-41 Steel gears energy consumption by scenario and by process

END OF LIFE STRATEGIES	PARAMETERS	STEEL PROCESSES					
		2,1	2,2	2,3	3,1	4,1	4,2
DISPOSAL STRATEGY	PROCESS	Sinter making	Iron pig making	steel making	XXX	Cylinder casting	Steel gear Machinng
	TYPE OF FUEL	77% Coke 3% Gas 20% Elec	70 % Coke 10% Gas 20% Other (Coal, El., oxy…)	1/3 Oxygen 1/3 Electricity 1/3 other (coal, gas…)	N/A	Electricity	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	135	4000	350	0	1680	50
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	486	14400	1260	0	6048	180
RECY STRATEGY	PROCESS	Sorting	XXX	XXX	Steel melting	Cylinder casting	Steel gear Machinng
	TYPE OF FUEL	Electricity	N/A	N/A	60% Electricity 40% Other (Oxygen, graphite, gas…	Electricity	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	730	0	0	700	1680	50
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	2628	0	0	2520	6048	180
REMAN. STRATEGY	PROCESS	Sorting	Cleaning	XXX	XXX	XXX	Steel gear remachinng
	TYPE OF FUEL	Electricity	Electricity	N/A	N/A	N/A	Electricity
	ENERGY CONSUMPTION *[kWh/ton salable aluminum]*	730	4	0	0	0	8
	ENERGY CONSUMPTION *[MJ/ton salable aluminum]*	2628	14,4	0	0	0	28,8

Figure 5.26 and Figure 5.27 illustrate the energy consumption given previously. These two diagrams classify the processes by their energy consumption. The energies are given in the decreasing order. These diagrams help to point the high energy consuming processes and therefore will be necessary to draw conclusions about end-of-life strategies environmental impacts.

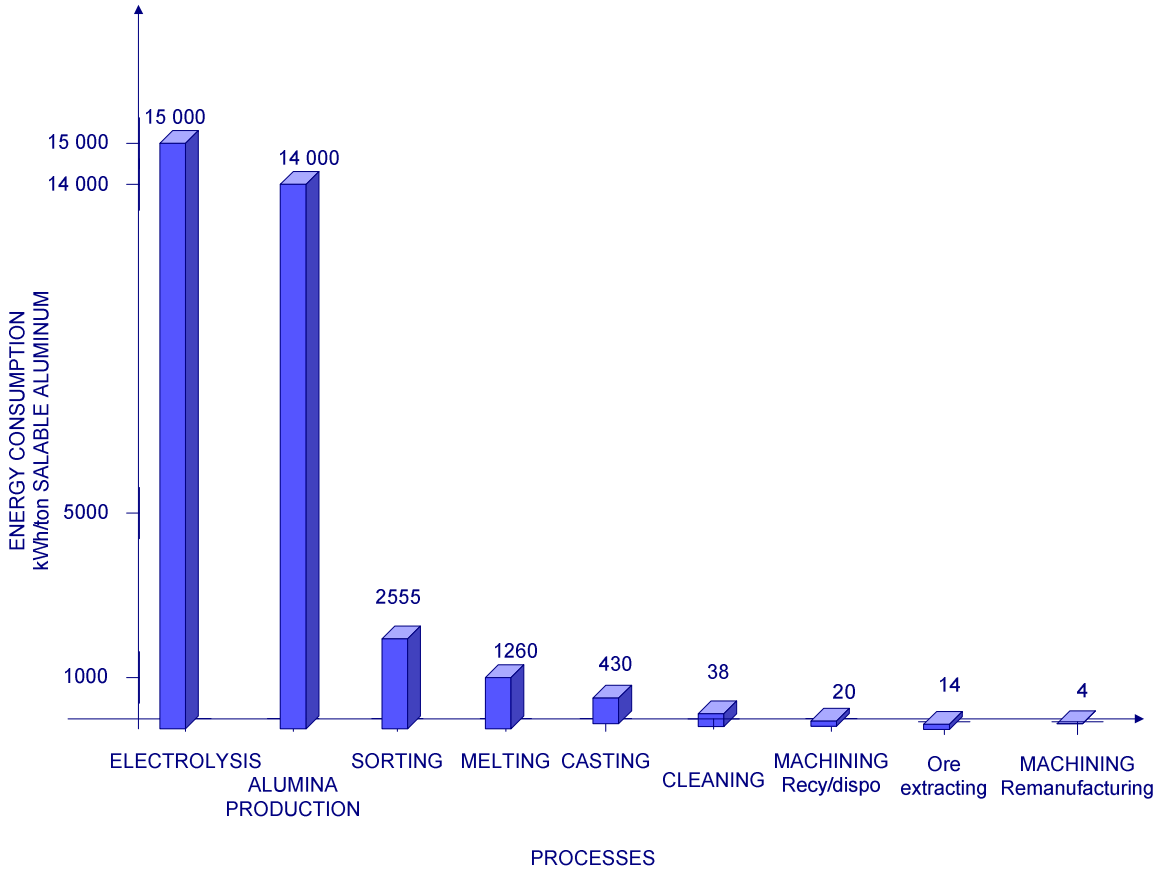


Figure 5-28 Aluminum energy consumption by process

Electrolysis and alumina production, present in the disposal strategy are the most energy consuming, followed by sorting processes, present in recycling and remanufacturing.

Melting and casting are part of disposal and recycling processes and precede the less energy consuming phase, which is the machining process, present in the three strategies.

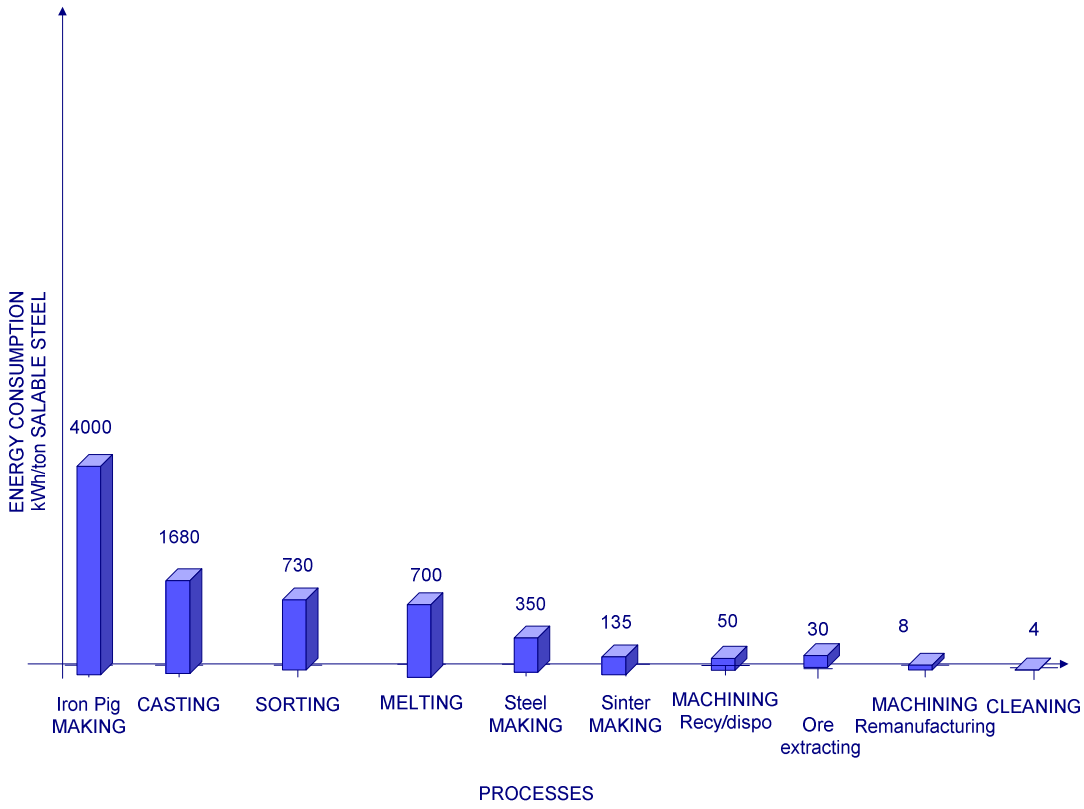


Figure 5-29 Steel processes ordered by energy consumption

CHAPTER 6

TRANSPORTATION ENERGY CONSUMPTION INVENTORY ANALYSIS

The previous study helped to evaluate the energy consumption of the three end-of-life strategies. The first phase of raw material supply has been purposely postponed because of the specific attention required by transportation, necessary to supply raw or primary material to the processing plant. The 6th chapter is a study of the transportation necessary in phase 1: Raw material supply.

6.1 Phase1: Raw material supply

6.1.1 DS Phase 1, transportation energy consumption analysis

6.1.1.1 Aluminum (DS) process 1.1 and process 1.2: Bauxite mining and shipping

Bauxite mines are mainly located outside the United States. The biggest exporters are Australia (with 60,000 tons/year 2001), Guinea, Brazil and Jamaica (with 11,000 tons/year 2001). Because of boats higher efficiency compared to trains or trucks and because of the long distances between Bauxite mines and US Aluminum plants, maritime transportation is preferred for disposal strategies. This is the transportation "best case" in term of energy consumption. Mining includes grinding, which is necessary to prepare ore for the alumina production phase and transportation from the mine to the shipping point. The energy consumption of the mining phase has been estimated thanks to a study realized in an Indian mining infrastructure (International aluminum institute 2004). In this

study, several mine infrastructures have been studied. The distance between these mines and shipping points are between 10 and 200 km. The number of mines in function of their distance from a shipping point are determined Figure 6.1.

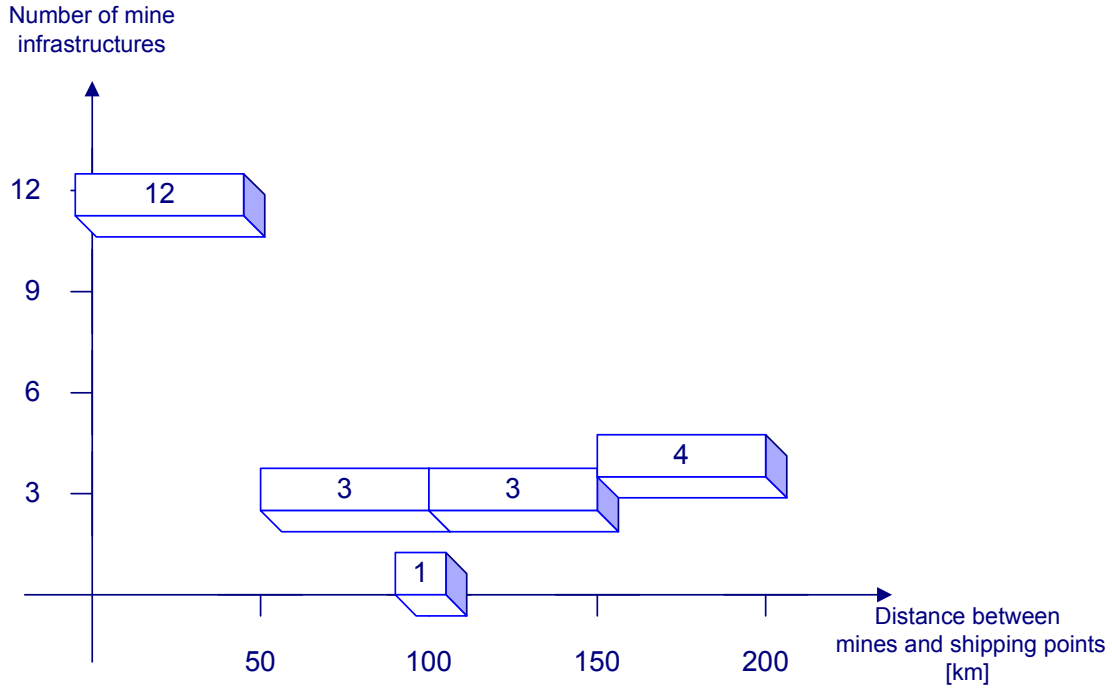


Figure 6-1 Aluminum mines geographical localization

Considering the mine infrastructure given figure 6.1, the energy consumption is between 13 and 231 MJ (3.6 kWh to 64 kWh) per ton of Bauxite. Given the fact that 4 tons Bauxite give 2 tons of Alumina, which give 1 ton salable aluminum, the corresponding energy varies from:

$EN_{mining}\,\min = 3.6 \times 4 = 14.4$ kWh/*ton salable aluminum* [6.1]

$EN_{mining}\,\min = 64 \times 4 = 256$ kWh/*ton salable aluminum* [6.2]

For transportation distances varying between 0 and 200km (Figure 6.1) including extraction processes, the resulting energy consumption is between 14.4 kWh/*ton salable aluminum* and 256 kWh/*ton salable aluminum*. As shown Figure Considering a linear increase of the energy consumption depending on the distance as represented in Figure 6.2, the global energy consumption of mining is given Equation 6.3, where x is the distance between mine and shipping point:

$$EN_{\text{mining Aluminum}} = 14 + \frac{253-14}{200-0}\,x = 14 + 1.195\;x \qquad [5.3]$$

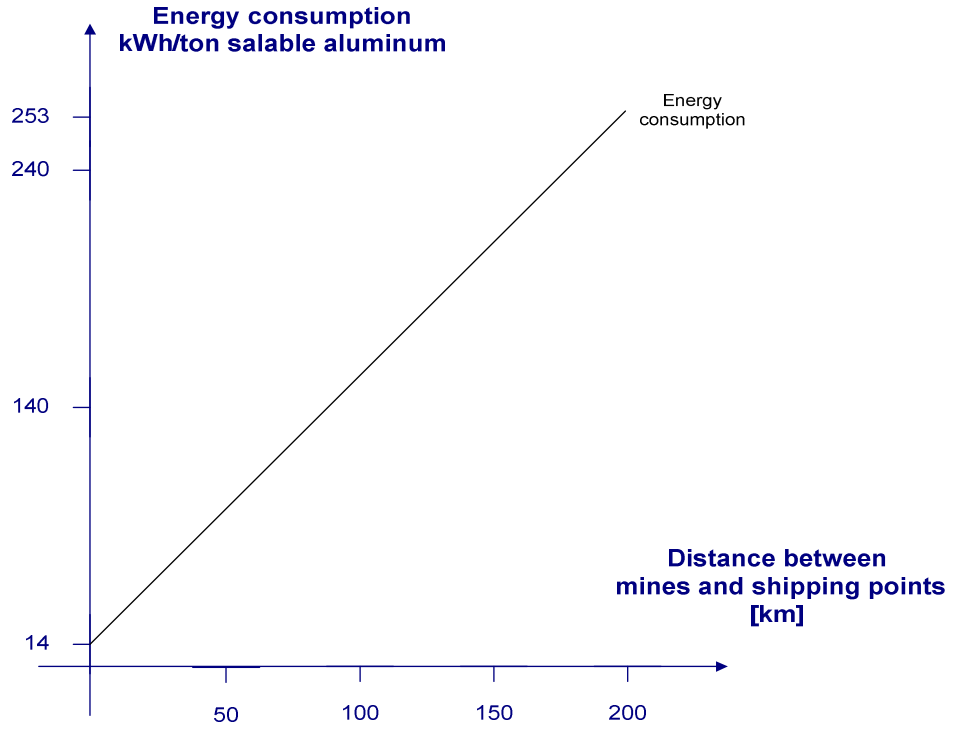


Figure 6-2 Aluminum ore transportation energy consumption linearization

The main fuels required for the extraction and heating is coal (5%) and fuel oil (25%). The transportation in the mine and to the shipping point requires diesel (70% of the

mining energy consumption) (International aluminum institute 2004). To conclude, given the fact that mines are usually located in a perimeter of 300 km from the shipping point, the maximum energy consumption required from the extraction process is estimated at 255 *kWh/ton salable aluminum.* In order to verify this assumption, Jamaica has been taken as example. This application is justified given the fact that Jamaica is a high producer of Bauxite, ranked in the fist places with Australia, china and Guinea (Geosciences Australia 2002). Figure 6.3 determines a map of Jamaica and the location of the bauxite mines and the shipping pier of the country.

Figure 6-3 Jamaican bauxite mining location (http://maps.google.com/)

Jamaica is one of the larger Bauxite suppliers for US. The Jamaican mines are located in a perimeter smaller than 300km and therefore verifies the previous assumptions. These mines have been located thanks to a research of extraction companies on the yellow pages and a map request (http://maps.google.com/) with the corresponding names.

The energy consumption of raw material transportation from the shipping point to the processing plant will be determined in the following section dedicated to transportation.

6.1.1.2 Steel gear (DS) process 1.2: Raw material supply

Iron mines are present in the United States. The extractions sites are located around the great Lakes in Minnesota and Michigan (Minnesota 2007) (USGS minerals 1998). The energy consumed by Iron ore shipping is going to be studied in the following section dedicated to transportation.

6.1.2 RS phase 1, energy consumption analysis

6.1.2.1 Aluminum and steel RCS process 1.1: used material collection

In recycling strategies, recyclable waste is collected from houses, landfills and plants to be brought to one shipping point. This first process can be performed by customers bringing used items to stores, municipal waste collection performed by professionals… This first process depends on items lease policies and contracts. It is the topic of many other studies performed in the SDM lab. Lease and return strategies will therefore not be studied here. This first process will be simply considered as a transportation phase where material is brought from a point A (retailers, houses, landfills, plants) to a point B (disposals). The energy consumption of used material transportation will be evaluated Section 6.3.3.

6.1.2.2 Aluminum and steel recycling RCS Phase 1.2: used material supply

In the recycling scenarios, the primary material is collected from disposals filled during the previous phase of material collection. The reusable material can also come from landfills. The distance between disposals and processing plants vary between recycling companies.

6.1.3 RMS phase 1, energy consumption analysis

6.1.3.1 Aluminum and steel RMS process 1.1: used parts collecting

Remanufacturing plants are less developed than recycling plants. Consequently there exist less collection sites, less circuits and less remanufacturing plants. Therefore, in order to be able to collect in different collectivities, remanufacturing plants are mostly located far from the cities. In this process, the energy consumption resulting from transportation of used parts will be evaluated.

6.1.3.2 Aluminum and steel RMS Phase 1.2: Used parts supply

In the transfer case remanufacturing scenarios, feedstock material is composed of transfer cases potentially assembled with other parts. In the steel gears, remanufacturing scenarios, the feedstock material is composed of steel gears. In fact, in remanufacturing end-of-life strategies, unlike recycling scenarios, the function of the part is not changed. This particular selection of used parts results in more elaborated collection scenarios and in longer collection distances. The energy consumption of transportation from parts disposals to remanufacturing plants is going to be evaluated in the next section.

6.2 Transportation energy analysis

The type of vehicle and media used for transportation depend on many criteria. Market, mines accessibility or plants capacity and locations are important to choose the right type of transportation. Water, air, rail and road are the most developed media. The study is restricted to US applications and therefore does not justify air transportation. In addition to that, the objective of the study is to minimize the energy use and the air pollution. Former researches proved that air freight is the most air pollutant vehicle with a low

transportation capacity. For instance, air freight emits 18 times more CO_2 than road freight (Facanha 2006). This is why air freight will not be included in this study. The three types of transportation that will be studied are:

- Truck or on-road vehicles
- Trains or rail vehicles
- Shipping boats or water vehicles

6.2.1 Assumptions on transportation vehicles

6.2.1.1 Trucks

In this study, trucks are supposed to transit via high ways. Given their different sizes and their consequently different environmental impacts, three categories of trucks are going to be studied. They are given Table 6.1(Ergudenler 2005). The categories are determined in function of trucks weight loading capacity. The weights of trucks are gross vehicle rate weight (GVRW). This defines the weight of a loaded truck. Category I is the smallest capacity starting at 3.5 tons. Category III represents the largest capacities that are up to 30 tons. Figure 6.4 shows the type and the appearance of the trucks given Table 6.1.

Table 6-1 trucks categories specification

Technical specification	Category definition	GVRW [kg]
HDDV2b	I	3500-4500
HDDV3-HDDV6	II	4500-12000
HDDV7-HDDV8b	III	12000-30000

Gross vehicle weight (lbs) *	VIUS categories	Vehicle type		
33001 or greater	Heavy heavy	 Dump	 Cement	 Heavy tandem conventional
26001-- 33000		 Fuel	 Recycling	 Medium conv.
19501--26000	Light--heavy		 Baverages	 Single van
16001--19500	Medium--Duty			
14001--16000				
10001--14000				Wide in van
6001--10000	Light-Duty			
6000 or less		pick up	Cargo van	Mini van
*Empty vehicle + payload				
** VIUS US Dpt of transportation Vehicle Inventory and used survey				

Figure 6-4 Transportation vehicles definition (Environment Canada 2002)

6.2.1.2 Trucks

A locomotive has a given maximum capacity of transportation. Nevertheless, the transportation is not always made of a unique type of part or material and ordered by one company. Thus, the whole capacity of a locomotive is not always exploited by one unique material or product. In order to avoid this uncertainty, the data concerning trains will be given for one locomotive and for one container of 30tons. A train is composed of many wagons with different sizes and different capacities. In 2004, in the US, the average of freight train carried 3100 tons of shipment and the average of wagons carried 60 tons of freight (Fletcher 2007). In order to be able to compare train to truck shipping, the

wagons are assumed to weight 30 tons. The assumptions about rail freight transportation are summarized Table 6.2.

Table 6-2 Train definition [Rail freight assumptions]

Freight mode	shipment load [tons]	Wagon load [tons]
Train	3200	30

6.2.1.3 Shipping boat

There are several types of boats with different applications. The most expended and used are cargo boats and barges. Barges are mostly used on rivers and inside seas. The data given in this research will be applicable on cargo boat because of their wide applicability in the industry. The average capacity of a US freight ship is 25,000 tons (US Department of Energy 2006). In this study, the shipment will be carried in containers. The average weight of these containers is assumed to be 30 tons. The assumptions about maritime freight are summarized Table 6.3.

Table 6-3 Boat definition [maritime freight assumptions]

Freight mode	shipment load [tons]	Container load [tons]
Boat	25000	30

6.2.2 Types of fuels used in transportation

In order to evaluate the energy consumption of each type of transportation and the resulting air emissions, it is important to define in a first time the fuel used by type of

vehicle. In fact, each fuel has its own heating value and therefore its own energy efficiency. In addition to that, the chemical composition of each fuel results in a specific emission. This is why it is capital to define the fu el used in the different freight modes.

6.2.2.1 Trucks

Most of heavy duty vehicles, since 1990, are diesel vehicles. In fact, Table 6.5, (Environmental Protection Agency 2001) shows that in 1990, diesel vehicle drove 80 % of the total miles traveled by whole trucks. In 2001 the total rate of miles traveled by diesel rises up to 85% of the total miles traveled by all trucks. Given the fact that trucks use exclusively one type of fuel without mixing it, and given the dominant use of diesel fuel, the study will focus on diesel trucks.

Table 6-4 Miles traveled by type of fuel and proportion of fuel use

		Vehicles Miles traveled for highway Heavy-Duty trucks (10^9 Miles)						
	Fuel type	TOTAL Miles traveled	Gasoline		Diesel		Alternative fuel	
			10 ^ 9 Miles	Percentage over global miles traveled	10 ^ 9 Miles	Percentage over global miles traveled	10 ^ 9 Miles	Percentage over global miles traveled
Year	1990	151.9	29.8	20%	121.2	79%	0.9	1%
	1991	155.3	31.7	20%	122.7	79%	0.9	1%
	1992	159.1	30.7	19%	127.6	80%	0.8	1%
	1993	166	29.8	18%	135.1	81%	1.1	1%
	1994	176.6	30.2	17%	145.4	82%	1	1%
	1995	184.5	30.1	16%	153.4	83%	1	1%
	1996	189.6	30.2	16%	158.3	83%	1.1	1%
	1997	198.3	30.1	15%	167	84%	1.2	1%
	1998	203.4	30.6	15%	171.5	84%	1.3	1%
	1999	210.4	30.8	15%	178.3	85%	1.3	1%
	2000	213.1	29.6	14%	182	85%	1.5	1%
	2001	214.8	28.5	13%	184.5	86%	1.8	1%

Derived form FHWA (1996 through 2002)

6.2.2.2 Trains and ships

Another data that confirms the major use of diesel by trucks is given by Table 6.5 (Davis 2006). This table gives also the type of fuel of the other transportation modes such as

train and ship. It appears that trains consume exclusively diesel fuel whereas freight boats consume 30 % diesel fuel and 70% of residual fuel. This information will be useful in the following study while determining energy consumption and air emissions.

6.2.2.3 Summary of type of fuel used during transportation

Table 6.5 gives a global overview of fuels consumed in 2003 by the three US transportation studied here.

Table 6-5 Transportation consumption by type of fuel- 2003 (Trillion Btu)

		Gasoline	diesel fuel [138700 BTU/gal]	liquified petroleum gas	residual fuel [149700 BTU/gal]	Natural gas	Electricity	Total
Highway	Medium/ heavy trucks	516.8	4608.4	17.1	0	0	0	5142.3
Non-Highway	Water freight	257.8 [32% vol]			570.6 [68% vol]			828.4
	Rail freight class I		533.9				0	533.9

Given this table,

- 89% of the energy consumed over one year by trucks result from diesel use and 10 % from gasoline use. In the truck case, given the small proportion of gasoline use and the fact that trucks use exclusively diesel or gasoline (no mix), only trucks consuming diesel will be taken in consideration in this study.
- 100 % of the energy consumed by freight train results from Diesel fuel.
- 30 % of the energy consumed by boat results from Diesel fuel use and 70% from heavy oil use. Given the fact that boat use a mix of diesel and heavy oil, the given proportion of fuel will be kept in the study.

6.2.3 Energy consumption resulting form transportation

Consumption of fuel has been judged as an efficient way to define the energy consumption of trucks, trains and ships. Thanks to the known price of oil, it will give an immediate idea of the cost of the energy, which is a commonly agreed upon value. In addition to that, it indicates the rate of fuel burnt in the engine. Thus, the energy can be estimated by the heating value of the combusted fuel. Some units used in this section may be confusing and therefore are given Table 6.6 (Environmental Protection Agency/Queensland Parks and wildlife services 2007).

Table 6-6 Units definition

Highway	Ton-Mile	The movement of 1 ton of cargo the distance of 1mile. Ton-Miles are calculated by mulltiplying the weight in tons of each shipment **transported** by the miles hauled.
	Vehicle Mile	Miles of travel by all types of motor vehicles.
Rail	Locomotive-Mile	The movement of a locomotive unit, under its own power, the distance of 1 mile.
	Train-Mile	the movement of a train which can consist of many cars, the distance of 1 mile.
Water	Ton-Mile	The movement of 1 ton of cargo the distance of 1 statute mile.

6.2.3.1 Trucks

Table 6.7 gives the diesel consumption of trucks (Ergudenler 2003). However these consumptions data are issued by a Canadian source these data are considered valid for US trucks.

Table 6-7 Fuel consumption by weight of truck

	Consumption		
Category (Table 1)	miles/gallon	L/km	L/100 km
I	9	0,265	26,5
II	7,1	0,33	33
III	4,7	0,5	50

Train and ship energy consumption will be evaluated with engine power and energy consumption. This is why their fuel consumption does not appear in this section. As mentioned before, the consumption of oil is a good indication to define the consequent use of energy. For instance, most of the diesels have a heating value around 38 MJ/L (Australian Government 2006) (DOB magazine 2007) (Davis 2006). Thus, the energy consumption of an engine is simply evaluated by multiplying the average consumption of the motor by the heating value of the fuel. The heating values of diesel and heavy oil are defined in Table 6.8 (Davis 2006).

Table 6-8 Heating value by type of fuel

Type of fuel	Heating value		
	[MJ/L]	BTU/gallon	kWh/L
Diesel	38	138 700	10.6
Residual oil fuel	42	149 700	11.8

The resulting energy consumption of the three categories of trucks (Table 6.1) are given Table 6.9.

Table 6-9 Energy consumption by size of truck

	Energy	
Category	BTU/mile	kWh/km
I	16,000	2.8
II	20,300	3.5
III	31,100	5.3

6.2.3.2 Train

Locomotive energy consumption is given for a 3200 tons loading Table 6.10. (Energy Information Administration 2006). Given the diesel heating value of 10.6 kWh/L and the 192 kWh/km energy consumption of a locomotive, the train mileage is 0.13 miles/gallon (18.1 L/km). Given the density of diesel 0.833 kg/L, the consumption is 15 kg/km of fuel.

Table 6-10 Energy consumption of a freight train

	Energy consumption						
	BTU/ton-mile	kWh/ton-km	BTU/loco-mile	kWh/loco-km	loco-miles/gallon	L/loco-km	kg/loco-km
Train	357	0.06	1,106,700	192	0.13	18.1	15

6.2.3.3 Ship

Water freight energy consumption is 253 BTU/ton-mile (0.045 kWh/ton-km) (US Department of Energy 2006). Given the average loading of 25,000 tons of shipment for a cargo boat, the energy consumed is 6.3 Million BTU/vessel-mile (1125 kWh/vessel-km). Table 6.11 summarizes these data and gives also the mileage 0.02 miles/gallon of a 25,000 tons freight boat.

Table 6-11 Energy consumption of freight ship

	Energy consumption						
Units	BTU/ ton-mile	kWh/ ton-km	BTU/ vessel-mile	kWh/ vessel-km	vessel-miles/ gallon	L/ vessel-km	kg/ vessel-km
Water freight	253	0,045	6 325 000	1125	0,02	98,5	86,5

6.2.4 Conclusion on transportation energy consumptions

Direct comparison between boats, trains and trucks energy consumption is difficult. Thus, the comparison will be done on a same weight of material transported. This comparison is made table 12. It compares the energy consumed by the transportation of a 30 tons container with trucks, a train and a freight boat Figure 6.5 illustrates the results given Table 6.12.

Table 6-12 Energy consumption comparisons

	BTU/ vehicle-mile	kWh/ vehicle-km	MJ/ vehicle-km	BTU/ 30tons-mile	kWh/ 30 tons-km	MJ/ 30tons-km
Truck	31,100	5.67	20.412	31,100	5.3	19.08
Train	1,107,143	192	691.2	10,445	1.8	6.5
Boat	6,325,000	1125	4050	7,590	1.35	4.86

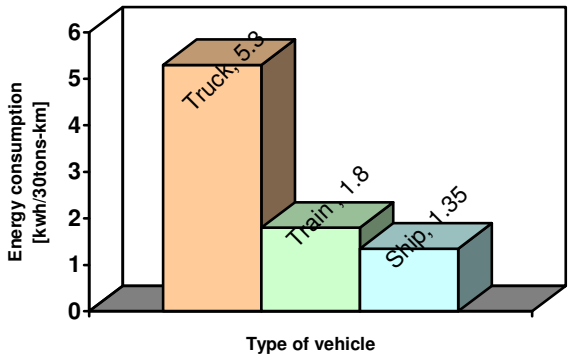


Figure 6-5 Energy consumption of freight transportation by type of vehicle

Given Table 6.12 numbers illustrated in Figure 6.5, it is possible to conclude that truck transportation consumes more energy than train and ship. In fact, it appears that a 30 tons container transported by a truck consumes three times more energy than a 30 ton container shipped by train and four times more energy than a 30tons container transported by ship. Nevertheless, conclusion about the type of transportation that has to be chosen for end-of-life strategies need to go more in depth of the scenario's context. In fact, as mentioned before, many other parameters such as plant accessibility, location or capacity influences the choice of transportation.

6.3 Global strategies energy consumption analysis

6.3.1 Transportation in end-of-life strategies

In the current study, transportation is assumed to be necessary exclusively in the first phase. In fact, all other processes (phase 2 to phase 4) are assumed to be realized in a same plant and do not require significant transportation.

In disposal scenarios, transportation is needed from the mine to the manufacturing plant. This is the process 1.2. In re-use strategies such as recycling and remanufacturing end-of-life strategies, transportation is used in process 1.1 and process 1.2. In fact, as it is shown Figure 6.6, a first transportation is required from the different producers of waste (point A) to a common shipping point (point B). This is process 1.1. The second transportation needed begins from on the shipping point to the re-use plant. It is process 1.2.

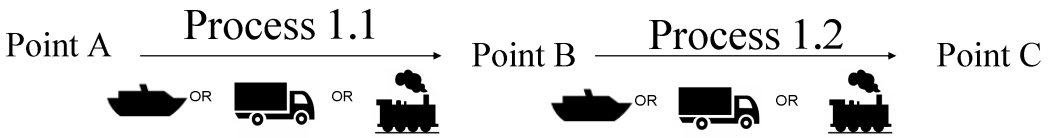


Figure 6-6 phase 1 transportation itinerary

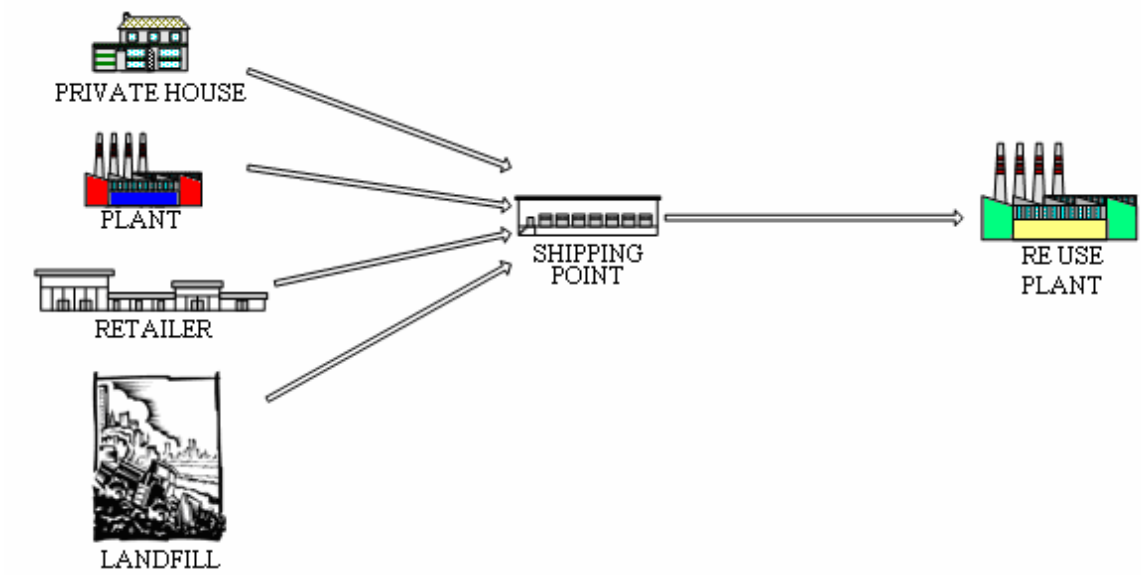


Figure 6-7 Phase 1 transportation circuit illustration

In the case of reusing strategies, the collecting process 1.1 plays a very important role in the environmental impact because of the transportation it requires. Nevertheless, the impact depends on strategies used by municipalities and companies. This topic is the focus of other independent researches currently preformed and therefore will not be considered in this study.

6.3.2 Transportation energy consumption

The energy consumptions given in Table 6.13 will be used in this analysis. These results are given in kWh/ tons-km. They result from the energy consumption calculated in Table

6.12. In order to be realistic, the shipments are assumed to be shipped with a full loading. The following energy consumption rates will be used for the calculation.

Table 6-13 Fuel consumption rate by freight vehicle type [kWh/ton –km]

Process	Type	Energy consumption
Tranportation [kWh/ton-km]	Truck	0.18
	Train	0.06
	Ship	0.045

It is important to notice that the energy consumption rate given in table 13 is given in kWh/ton transported-km and not kWh/ton salable material–km. The energy consumptions given in Table 6.13 depend on the distance covered by the vehicle and also on the mass transported. The quantity of salable material present in this mass varies between the end-of-life scenarios. In fact, in the case of disposal strategies, ore has to be transported to processing plants, where the pure material is extracted. In this case, more material is transported than pure material is sold. In the case of reusing strategies, the amount of reusable material in the supply vehicle depends on the preliminary sorting that has been performed in the collecting process 1.1. Therefore, the model developed in the next section will help to evaluate the energy consumption of the strategies in function of the distance covered by the supplying vehicle but also by the amount of salable material actually present in the container.

6.3.3 End-of-life strategies energy consumption model

The following is a model that determines the energy consumption *EN* of each end-of-life strategy in function of the distance noted x, covered during the raw material supply phase

and also the proportion of salable material y. The energy consumption and the x and y parameters are defined for each end-of-life strategy as following:

6.3.3.1 DS process 1.2: Raw material supply

In the case of disposal strategies, 4 tons of ore are necessary to produce 2 tons of Alumina and consequently 1 ton of salable Aluminum. Thus, a container supplying ore to aluminum processing facilities will only transport 25% of salable aluminum, which results in $y_1 = 0.25$.

In the case of disposal strategies, 1.4 tons iron ore are necessary to produce 1 ton of steel. Thus, a container supplying ore to steel processing facilities will transport 70 % of salable steel, which results in $y_1 = 0.70$.

The transportation energy rates or *ENr* resulting from Equation 6.2 for aluminum and steel applications are summarized Table 6.14.

$$\text{Energy rate} = Transportation\ energy\ consumption \times \frac{1}{y_1} \quad [6.2]$$

Table 6-14 Energy rate by type of transportation

Transportation type	Auminum energy rate ENr	Steel energy rate Enr
Truck	0.72	0.257
Train	0.24	0.085
Ship	0.18	0.064

The disposal strategy global energy consumption resulting from the four phases is given Equation 6.3.

$$ENDS = \sum_{k=1}^{k=4} ENDS_{phasek} \quad [6.3]$$

$$ENDS = 29470 + EN \times \frac{x_1}{y_1}$$

Figure 6.7 is an example of recycling energy scenarios where aluminum is transported with ships at a mass rate of y_1 equal to 0.25. The behavior of steel energy consumption ($y_1 = 0.70$) is similar and therefore is not displayed here.

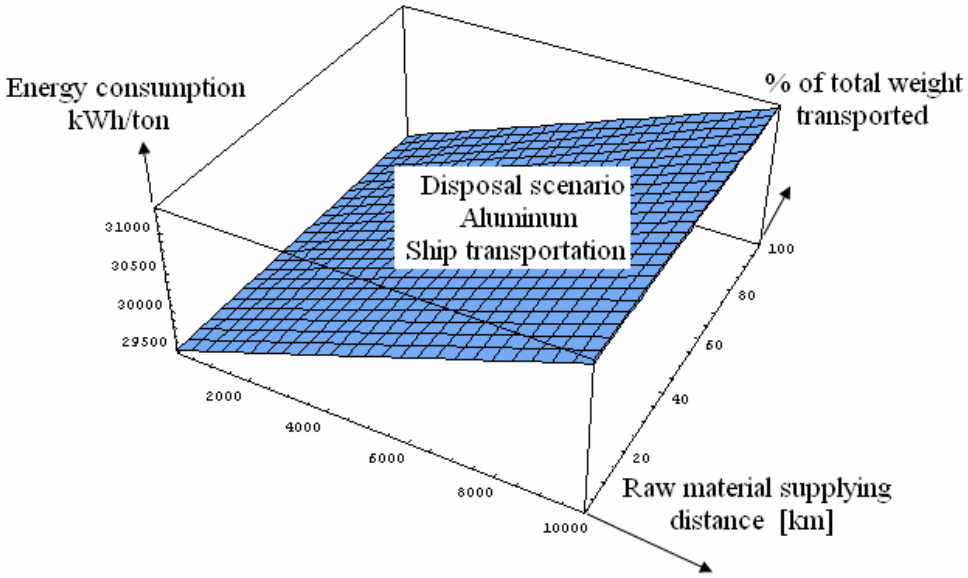


Figure 6-8 Aluminum DS energy consumption, ship transportation

6.3.3.2 RCS process 1.2: Used material supply

Disposal strategy's shipping has a constant mass rate of aluminum. It is different in the case of recycling. In fact, shipments might contain different amount of recyclable material depending on the preliminary sorting performed in the collecting process (1.1). The mass rate of recyclable material in the shipment is defined by y2 and calculated Equation 6.4.

$$y_2 = \frac{Mass_{recyclablealum}}{Mass_{container}} \quad [6.4]$$

The recycling strategy global energy consumption resulting from the four phases is given Equation 6.5 and illustrated Figure 6.8. The energy consumption ENC is given in function of the percentage of recyclable material y_2 in the shipment and in function of the distance x2 covered by the supplying ship.

$$ENC = \sum_{k=1}^{k=4} EN\ \ RCS_{phasek} \quad [6.5]$$

$$EN\ \ RCS = 4225 + EN(\frac{1}{y_2}) \times x_2$$

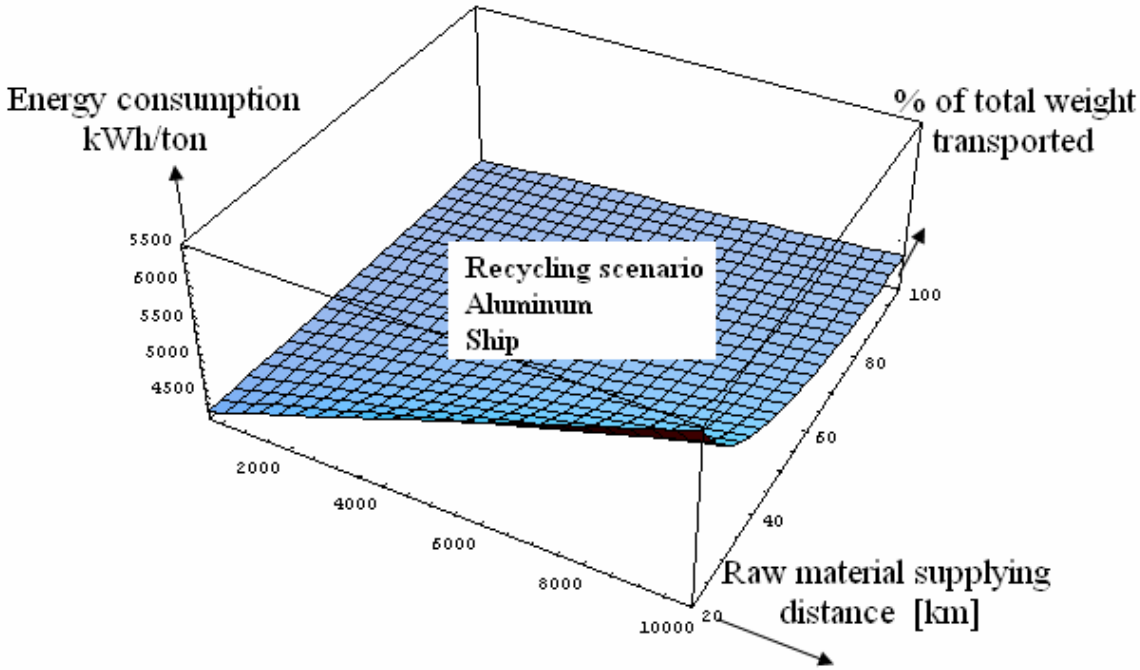


Figure 6-9 RCS energy consumption, function of distance and aluminum transportation mass rate

6.3.3.3 RMS (1.2): Used part supply

As in the recycling scenarios, the amount of remanufacturable material in the shipments varies. Here, the mass rate y3 of reusable material transported is given by Equation 6.6.

$$y3 = \frac{Mass_{remanufacturablealu\min um}}{Mass_{container}} \quad [6.6]$$

In the case of transfer case housings, an y3=1 would represent shipping containing only aluminum transfer cases. This would be an ideal case suggesting that the trucks transmissions would have been disassembled before shipping. Remanufacturing and recycling collection is assumed to be performed by 30 tons trucks via road. The remanufacturing energy consumption ENR is given Equation 6.7 and illustrated Figure 6.9. The *x3* parameter is the distance covered by shipping and *y3* is the mass rate of aluminum in the shipment.

$$ENR = \sum_{k=1}^{k=4} EN\ \ RMS_{phasek} \quad [6.7]$$

$$ENR = 2597 + EN(\frac{1}{y3}) \times x_3$$

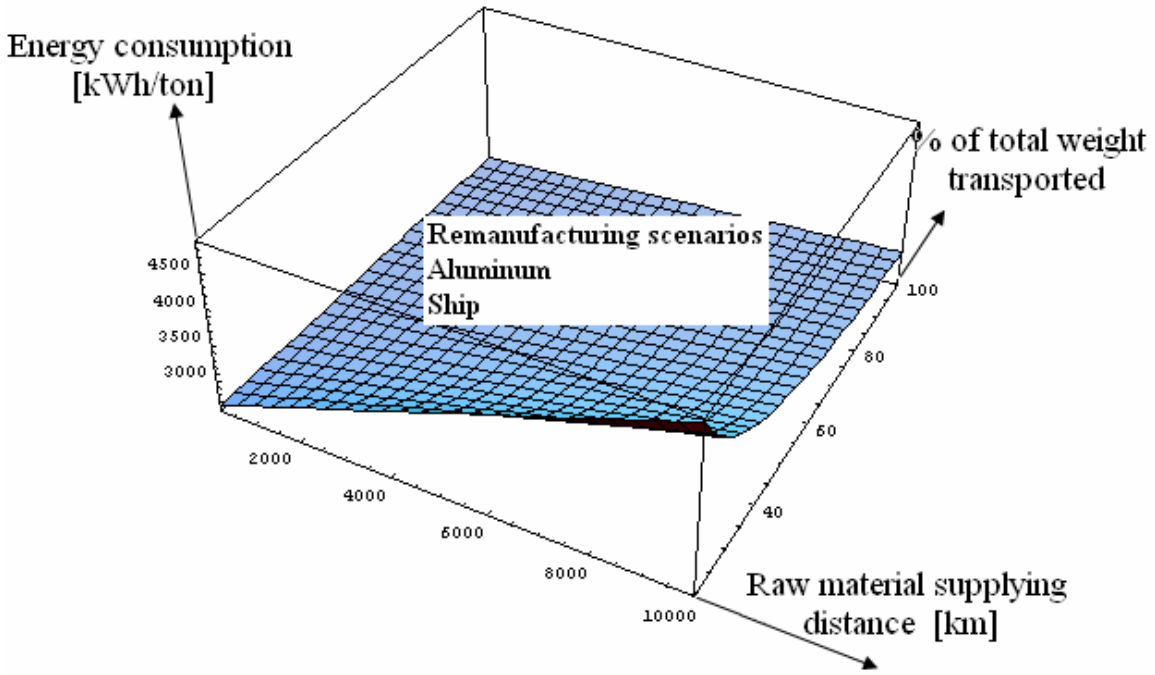


Figure 6-10 Remanufacturing scenarios energy consumption

6.3.4 Comparison of the three strategies energy consumption

Table 6.15 summarizes the energy consumption of the three strategies in function of y_i [i=1,i=3] and xi [i=1, i=3] the distance covered by transportation.

Table 6-15 Energy consumption of the three end-of-life strategies

Scenario	Energy consumption equation
Disposal	29470+EN (1/y1) x1
Recycling	4225 + EN (1/y2) x2
Remanufacturing	2597 + EN (1/y3) x3

The energy consumptions of recycling and remanufacturing scenarios evolve similarly. Disposal strategies energy consumption has another behavior because of the constant mass rate y_1. In fact, in aluminum as in steel cases, the method of metal refining is

standard and leads always to the same solid waste and use of natural resource. As it has been demonstrated, in the case of aluminum, $y_1 = 0.25$ and in the case of steel, $y_1 = 0.70$. Figure 6.11 displays disposal, recycling and remanufacturing scenarios simultaneously. This diagram draws the energy function of aluminum. However, the observations and comments made here are also applicable to steel where the curves have the same behavior. The differences between the two materials will follow these comments. On figure 6.11, a small transportation mass rate results in a dramatic increase of the energy consumption as distance covered increases. Whereas, over a given mass rate, the energy consumption of transportation remains almost stable with the distance covered. This is important information. In fact, a high mass rate implies sorting before shipping, and therefore requires special equipments. This might even require the presence of a sorting facility. On the contrary, low mass rate transportation does not require high quality sorting before shipping, therefore no special investment is required. For instance, municipal waste recycling makes use of low mass rate transportation. Each user (city inhabitant) performs a low quality sorting (recyclable versus non recyclable). Figure 6.11 show simultaneously the three scenarios energy consumptions respectively for aluminum and steel production.

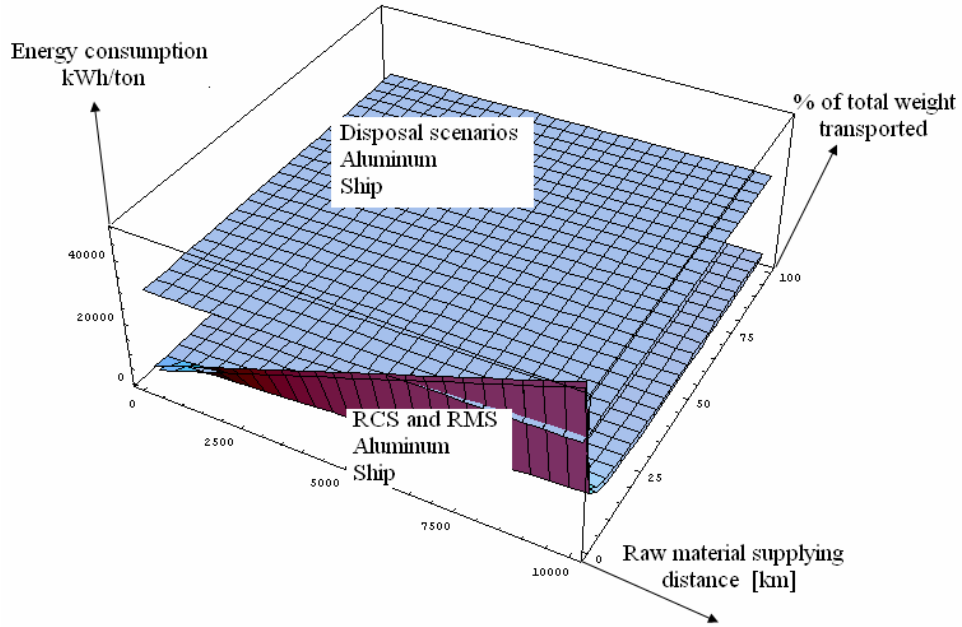


Figure 6-11 Aluminum three scenarios

Another point of view of the previous graph is given Figure 6.12 shows simultaneously the three scenarios applied to aluminum (figure 6.12.a) and applied to steel (Figure 6.12.b).

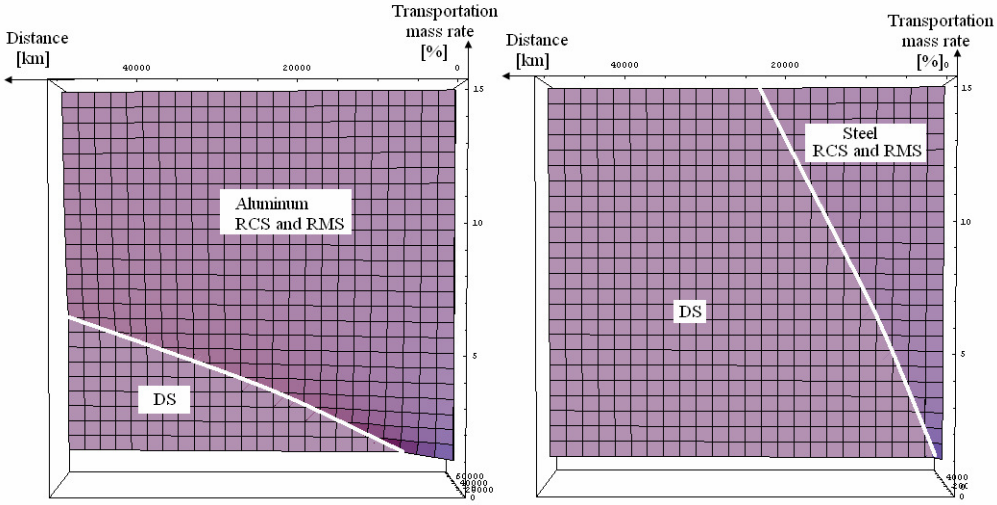


Figure 6.12.a Aluminum three scenarios **Figure 6.12.b Steel three scenarios**

Figure 6-12 Comparison of material's influence on energy consumption

The comparison between aluminum and steel scenario shows that the domain where disposal has lower energy consumption than reuse strategies is larger in steel scenarios than in aluminum scenarios. This is due to the fact that steel energy consumptions are closer between scenarios than in the aluminum case. In addition to that the mass rate of disposal is much higher in steel scenarios with 70% compared to aluminum disposal scenarios where mass rate is equal to 25%.

In the aluminum case study, the distance can be up to 6000 km without making the reuse strategies energy consumptions higher than disposal scenarios. In addition to that, over 6000km and until 50000 km, the minimum mass rate to avoid superior disposal energy consumption stays very low (6% maximum). Whereas in steel scenarios, the energy consumption is lower than reuse strategies as soon as the distance covered is higher than approximately 1200 km. Over this distance, minimum mass rate increases linearly to attain 100% at 24000 km. This important observation on steel scenarios means that over a supply distance of 24000km, the disposal scenarios have lower energy consumption than reuse scenarios.

Figure 6.12.a and Figure 6.12.b show an essential point about the impact of recycling (or remanufacturing) compared to disposal. It shows that for low mass rates, disposal strategies tend to be less energy consuming than recycling (or remanufacturing) strategies. As mentioned before, in the current municipal recycling strategies, Aluminum and steel are collected with other materials such as glass and paper. The weight proportion of aluminum and steel are between 1% and 1.5% of the total collection (Dreamsam Recycling Group 2007) (Environmental Protection Agency 2006) .In this case, to be interesting from energy point of view, figure 6.12.a and Figure 6.12.b show

that recycling strategy should have a maximum collection circuit of approximately 6000 km for each ton of aluminum and 2000 km for each ton of steel.

To conclude, if disposal end-if-life scenarios have global energy consumption much more important than recycling scenarios and remanufacturing scenarios as it is the case in aluminum transfer cases, then transportation is not likely to negatively influence the energy savings of reuse strategies. On the contrary, if scenarios global energy consumptions are close as it is the case in steel gears scenarios, a bad management of transportation is more likely to annihilate the energy savings of reuse strategies. In the case of close energy consumptions, material sorting should preferably be performed before material shipping.

In figure 6.12, the material supply was realized by ship. Figure 6.13.b shows simultaneously the three end-of-life scenarios energy consumption supplied by train (EN = 0.06). The following Figure 6.13.a shows simultaneously the energy consumption of the three end-of-life scenarios supplied by truck (EN = 0.18).

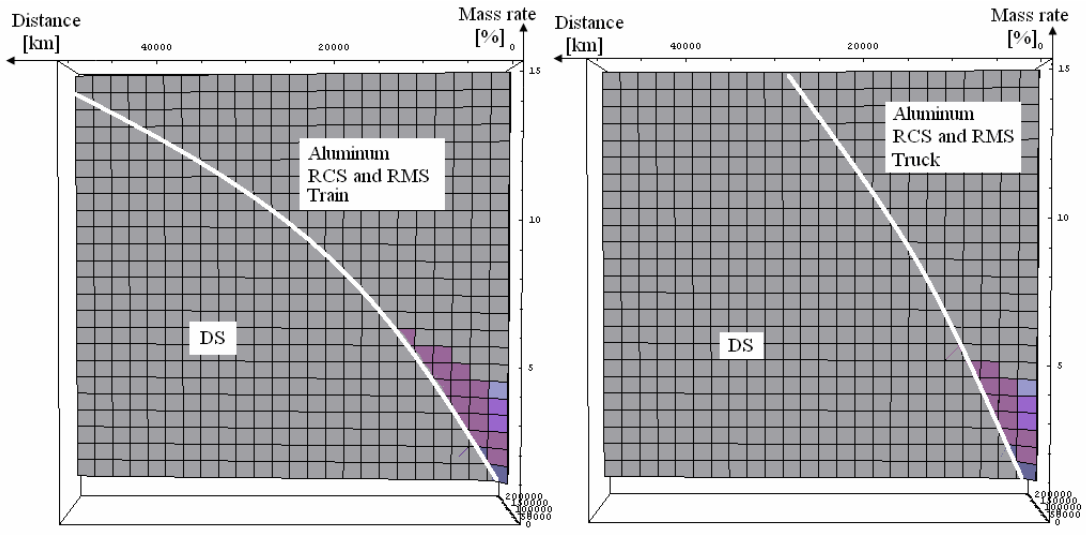


Figure 6.13.a Aluminum scenarios, train supply **6.13.b Aluminum scenarios, truck supply**

Figure 6-13 Comparison between transportation vehicle's influence on energy consumption

Figure 6.13.a and 6.13.b show that the domain where reuse strategies consume less energy than disposal scenarios is smaller with train supply than with truck supply. This leads to the conclusion that low mass rate shipments resulting from the absence of preliminary sorting may alter the energy savings benefits of reuse strategies. Nevertheless, this study does not consider the rest of the transportation loading that can be reused as well. In fact in the case of transmissions not disassembled before shipping, the aluminum transfer case shipment has low aluminum mass rate because of the other dense components such as steel parts that are simultaneously shipped. However, these other dense part might also be reusable and therefore change mass rate of reusable material present in the shipment. The reuse of other parts than aluminum transfer case issued from the same shipment would positively change the conclusions about energy savings. However, reuse of part with different functions and different materials require various equipment and techniques in a same plant. The machines and process costs could be dramatically increased. This could be the focus of a future research.

6.4 Transportation simulation

6.4.1 Aluminum transfer case application

In this chapter, transportation has been demonstrated to play an important role in the scenarios energy consumption. This section is dedicated to apply the model developed previously on an industrial application case study. The energy efficiencies are given Table 6.16.

Table 6-16 Transportation modes efficiencies

	Transportation type	kWh/ton-km
Transportation energy rate	Truck	0.180
	Train	0.060
	Ship	0.045

6.4.1.1 Remanufacturing scenario (RMS)

A company named "TECH" would like to remanufacture transfer case housings. The primary manufacturer is located in Bordeaux (France, EU). TECH Company is located in St Louis Missouri. The itinerary to transport the parts from Bordeaux to TECH company is given Table 6.17. Transports are usually chosen for their rapidity or their low cost. This depends on the priorities of the companies (AMTRAK 2007).

Table 6-17 Aluminum RMS transportation itinerary

Transportation order	Departure	Arrival	Transportation mode	Energy efficiency [kWh/ton-km]
1	Bordeaux, plant	Bordeaux, harbor	Truck	0.18
2	Bordeaux harbor	NYC harbor	Ship	0.045
3	NYC harbor	NYC train station	Truck	0.18
4	NYC train station	Chicago (IL) train station	Train	0.06
5	Chicago, train station	St Louis train station	Train	0.06
6	St Louis, Train station	st Louis, plant	Truck	0.18

Table 6.18 gives the distances and the reusable mass rates of the different transportation phases.

Table 6-18 Aluminum RMS distances and mass rate of transportation phase

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0,18	0.08	50
2	0,045	0.08	10000
3	0,18	0.4	50
4	0,06	0.4	650
5	0,06	0.4	750
6	0,06	0.4	500
7	0,18	0.4	50
TOTAL			12050

In this scenario, the transmission trains are shipped in one peace over the Atlantic and then partially separated. The transmission is assumed to be separated at the arrival in the US before being shipped to the remanufacturing plant. The resulting energy consumption is given Figure 6.14 in function of the distance covered.

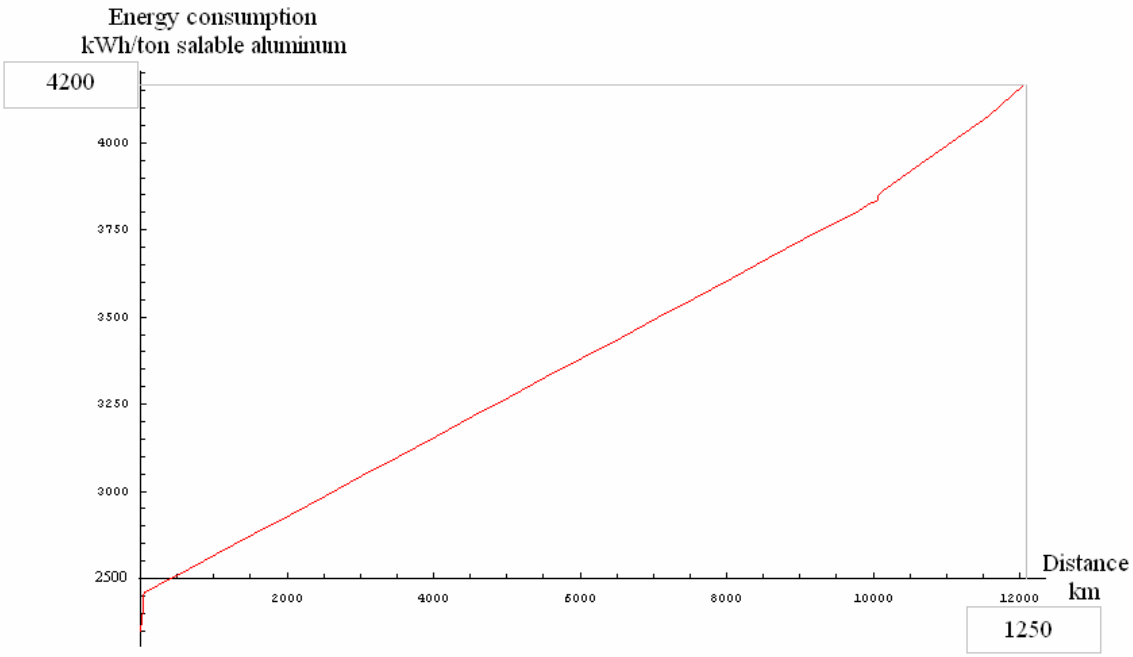


Figure 6-14 Remanufacturing energy consumption

In Figure 6.14, the function's slope changes at distance x = 50 km, x = 10050 km, x= 10100 km and x=12000 km. These changing of slope (non-derivable points) show where transportation type change. This graph shows graphically the energy consumption of remanufacturing strategy corresponding to the itinerary determined Table 6.18. The energy consumption is approximately 4200 kWh/ton aluminum.

6.4.1.2 Recycling scenario (RCS)

If the company decided to use recycled aluminum to produce transfer cases, the transportation itinerary would be different. In fact, used aluminum can be purchased in many US States. A lot of recycling plants exist in Missouri. One random recycling company has been used for this example. The locations of this recycling company's plants are shown Figure 6.15.

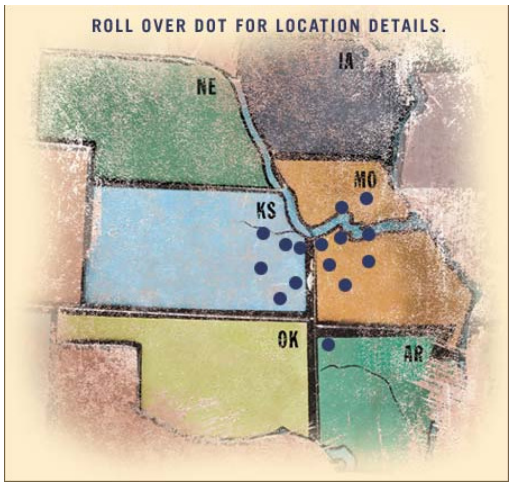


Figure 6-15 Recycling plants located in the area of St Louis, MO (Galamba Metal Group 2007)

In this case, aluminum is assumed to come only from municipal waste management. Solid waste is collected from residences or stores and transported to recycling facilities.

There, aluminum is extracted from the other waste such as glass or paper and sent to the St Louis transfer case manufacturing plant. The material is transported by truck. The collection phase is roughly evaluated at 1000 km. The distance between St Louis manufacturing facility and the recycling plant is also roughly estimated at 600 km. The itinerary is summarized Table 6.19.

Table 6-19 Aluminum RCS itinerary

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0.18	0.01	1000
2	0.18	1	600
TOTAL			1600

The energy consumption resulting from recycling scenarios is given in Figure 6.16 in function of the distance covered during the transportation phase.

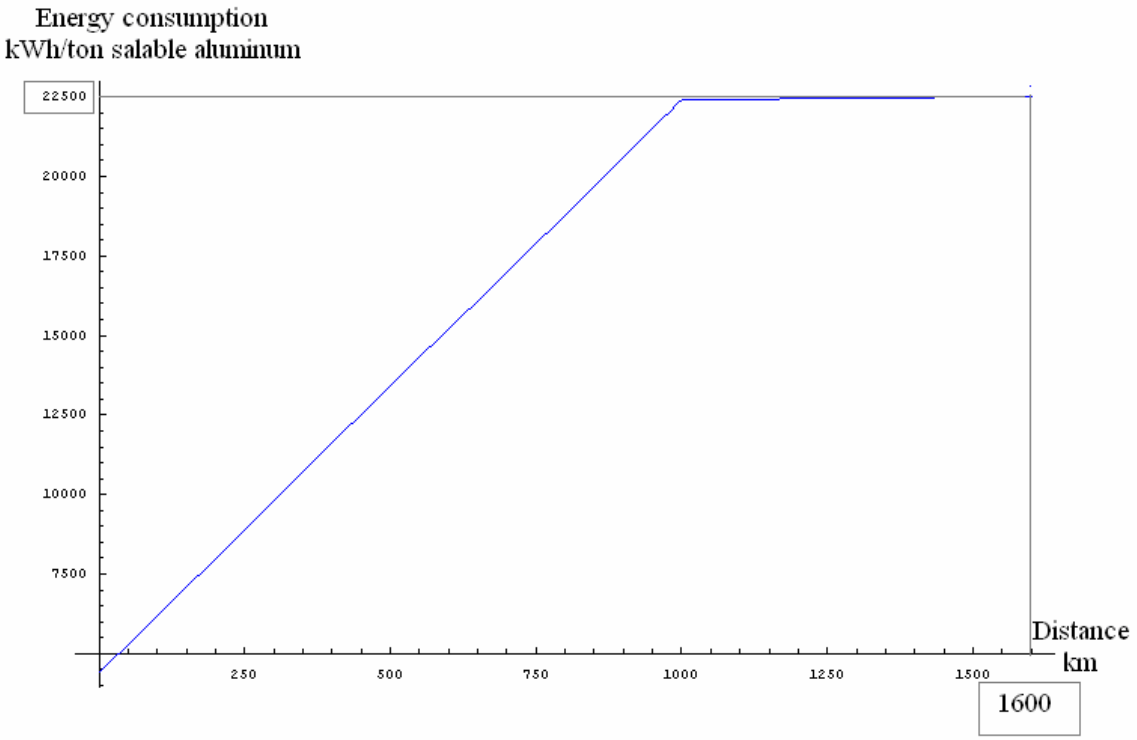


Figure 6-16 Aluminum recycling scenarios energy consumption

In Figure 6.16, the function's slope changes at distance x = 1000 km. This is not due to a change of vehicle type during transportation. In fact, in this scenario, material is always transported by truck. The slope changes because the aluminum mass rate increases from 0.01 to 1 at x = 1000 km. Aluminum sorting is performed at the recycling facility located 600 km away from the TECH facility. This is why the mass rate of reusable material transported in the last 600 km is equal to one and the transportation is much more efficient. The small slope between x = 1000 km and x = 1600 km corresponds to this high transportation efficiency. The total energy consumption of the aluminum recycling scenario is approximately 22,500 kWh/ton salable aluminum.

6.4.1.3 Disposal scenarios (DS)

As demonstrated before, the closest locations to purchase bauxite are Jamaica or Brazil. In this application, bauxite is purchased in Jamaica and transported to New Orleans by ship. It is then transported by truck to New Orleans train stations. Train is used to St Louis. The final transfer from train station to plant is performed by truck. The itinerary is given Table 6.20.

Table 6-20 Aluminum Disposal itinerary

Transportation order	Departure	Arrival	Transportation mode	Energy efficiency [kWh/ton-km]
1	jamaica, Mine	Jamaica, Harbor	Truck	0.18
2	Jamaica, Harbor	New Orelans, Harbor	Ship	0.045
3	New Orelans, Harbor	New Or., train station	Truck	0.18
4	New Or., train station	St Louis, train station	Train	0.06
5	St Louis, Train station	st Louis, plant	Truck	0.18

The distances covered depending on the transportation used are determined Table 6.21.

Table 6-21 Aluminum DS distances and mass rate of transportation phase

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0.18	0.25	50
2	0.04		1900
3	0.18		50
4	0.06		1150
5	0.18		50
TOTAL			3200

The energy consumption resulting from recycling scenarios is given Figure 6. in function of the distance covered during the transportation phase

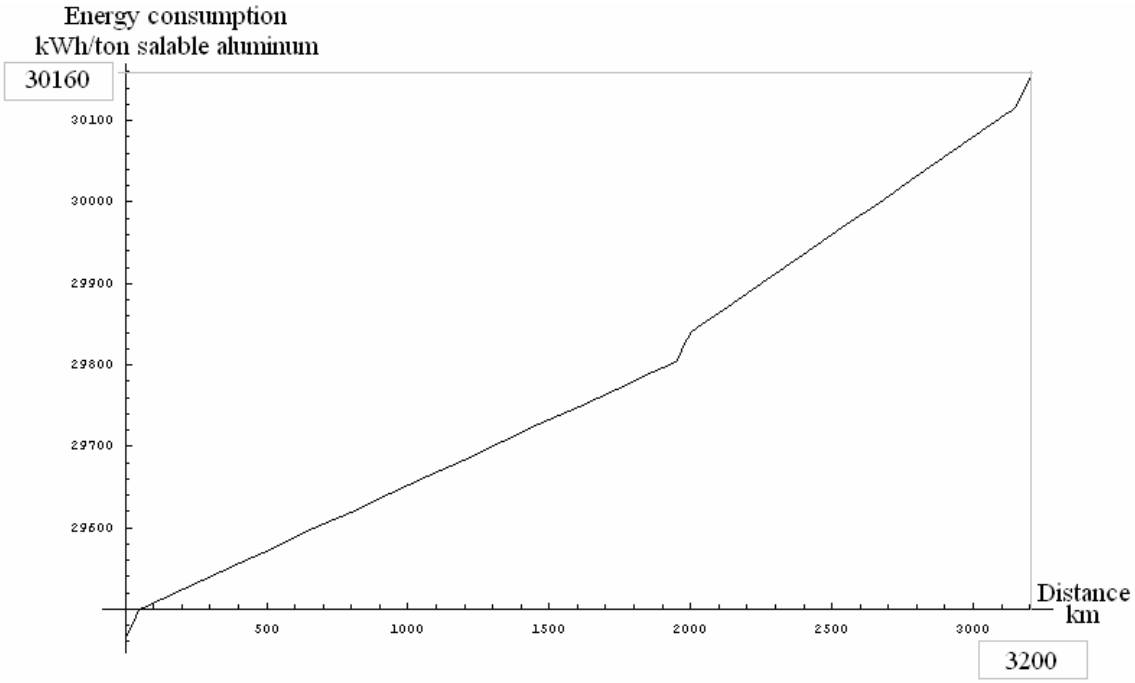


Figure 6-17 Aluminum disposal scenarios energy consumption

In Figure 6.17, the function's slope changes at each transportation type changing which corresponds to the distances x = 50 km, x = 1950 km, x = 2000 km, x = 3150 km. Given the fact that the usable mass rate is constant during the whole trip, there is no slope change corresponding to any sorting process. The total energy consumption can be read graphically and is approximately 30,160 kWh/ton salable aluminum.

6.4.1.4 Scenarios energy consumption comparison

Figure 6.18 graph is a superposition of disposal, recycling and remanufacturing scenarios.

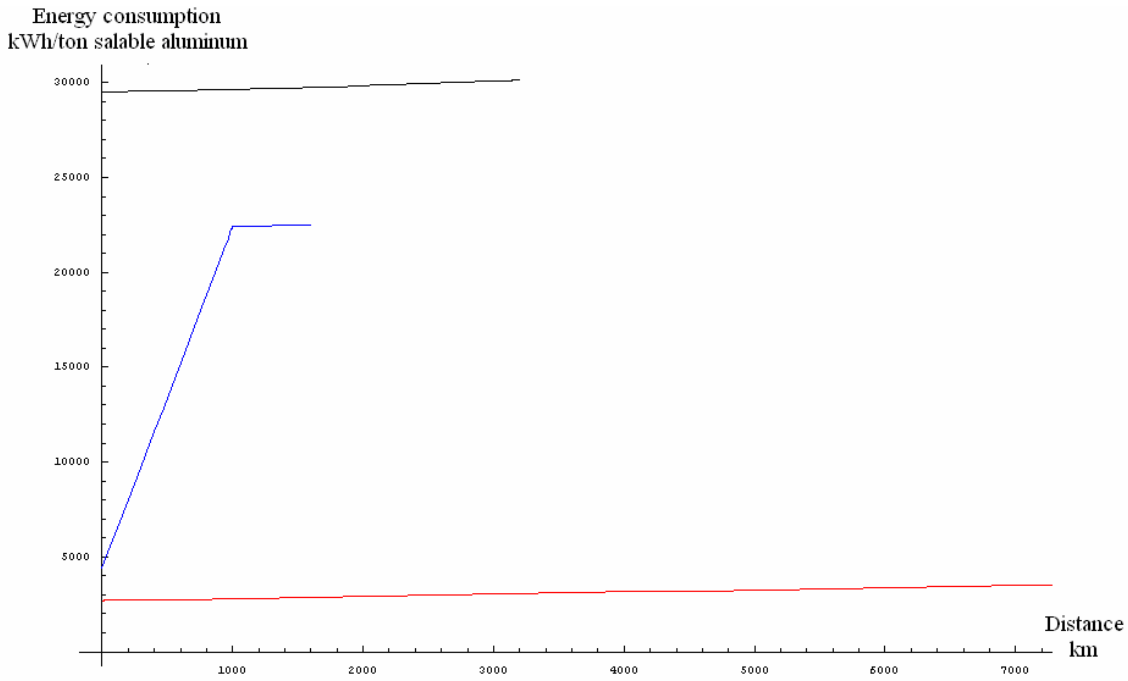


Figure 6-18 Aluminum three scenarios energy consumption comparison

In this case, the energy consumed in remanufacturing scenarios is lower than disposals and recycling scenarios. In this particular case, remanufacturing transfer cases would be advantageous from an energy point of view. Recycling scenario energy consumption is also lower than disposal. Therefore, recycling scenarios would also be more advantageous than disposal scenarios.

6.4.2 Steel gears application

6.4.2.1 Remanufacturing scenario

The same exercise is going to be performed for steel gears. As for aluminum housings, used steel gears are assumed to be shipped from Bordeaux in France. The itinerary used to supply the used part to the remanufacturing plant is the same as for aluminum parts.

The only parameter that changes here compared to the previous case is the mass rate in the shipping container. In fact, given the fact that steel density is 7.8 tons/cubic meters, it is approximately 3 times higher than aluminum density that is only 2.7 tons/cubic meters. Assuming that the volume of remanufacturable steel transported from Bordeaux to US is equal to the volume of remanufacturable aluminum transported in the previous application, the steel mass rate used here is 0.24. The mass rate during US transportation (rail and road), the mass rate remains 0.4. Table 6.22 gives the itinerary associated with the steel mass rate transported from Bordeaux to St. Louis.

Table 6-22 Steel RMS distances and mass rate in transportation phase

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0.18	0.24	50
2	0.045	0.24	10000
3	0.18	0.4	50
4	0.06	0.4	650
5	0.06	0.4	750
6	0.06	0.4	500
7	0.18	0.4	50
TOTAL			12050

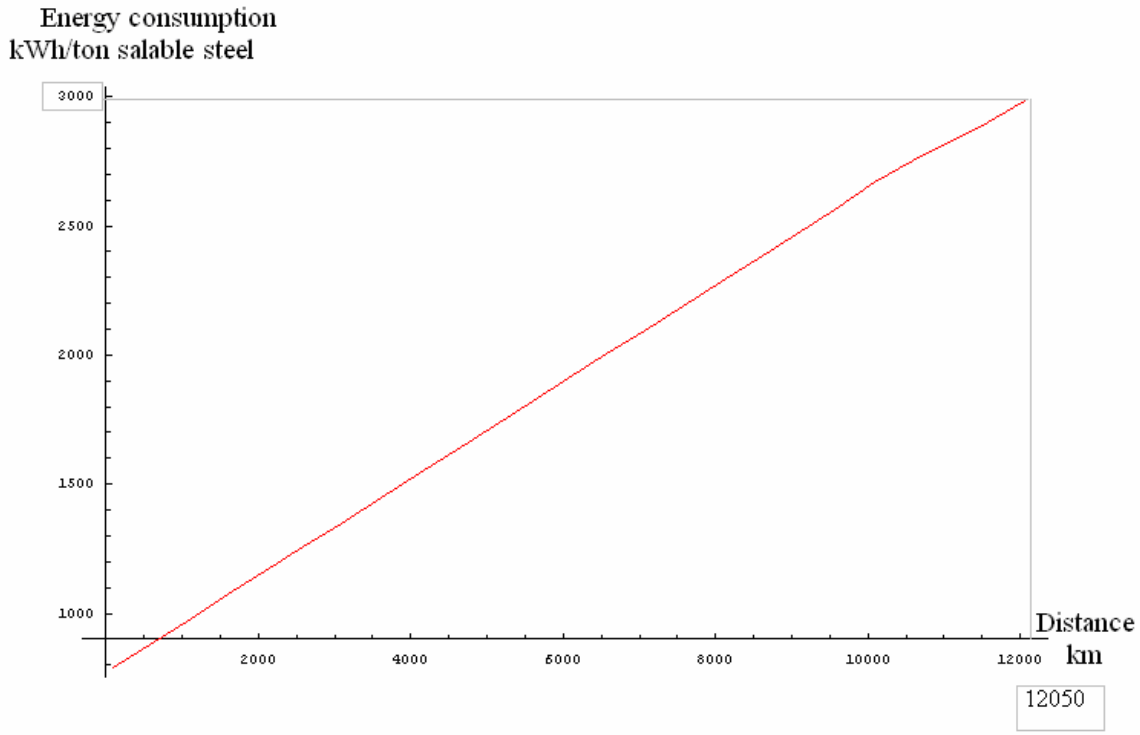


Figure 6-19 Steel remanufacturing energy consumption

In Figure 6.19, the slight change of slope at the distance x = 10050 km corresponds to a change of reusable material mass rate but also to a change of vehicle type. After 10050 km, the vehicle efficiency decreases (Change from ship to truck) and therefore, the slope should increase. Nevertheless, after 10050 km, the reusable material mass rate increases and therefore should decrease the slope of the function. The global result of these two changes is a slight decrease of the slope at x = 1000 km. The total energy consumption of steel recycling scenarios resulting from the itinerary determined Table 6.22 is approximately 3000 kWh/ton steel.

6.4.2.2 Recycling scenario

In the recycling scenarios, the transportation itinerary is the same as in the previous aluminum application. Steel used material comes from municipal waste where the steel

mass rate is 0.008 and also from car disposals where the mass rate is 0.77. The distance covered during municipal collection is 900 km. The trucks collect the waste of each residence in a given area. This complex circuit of collection results in higher distances traveled than in the case of car disposal collection. In fact, the distance covered during car disposal collection is 100 km. The used steel is collected in car disposal and brought to sorting facilities. The distance between the sorting facility and the manufacturing plant is 600 km.

Table 6-23 Steel RCS itinerary and types of vehicles used

Transportation order	Departure	Arrival	Transportation mode
1	Residences	Sorting facility, St Louis	Truck
2	Car disposal	Sorting facility, St Louis	Truck
3	Sorting facility, St Louis	Manufacturing plant	Truck

Table 6-24 Steel RCS Distances and mass rate in transportation phase

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0.18	0.008	900
2	0.08	0.77	100
3	0.18	1	600
TOTAL			1600

These parameters result in the graph given Figure 6.20.

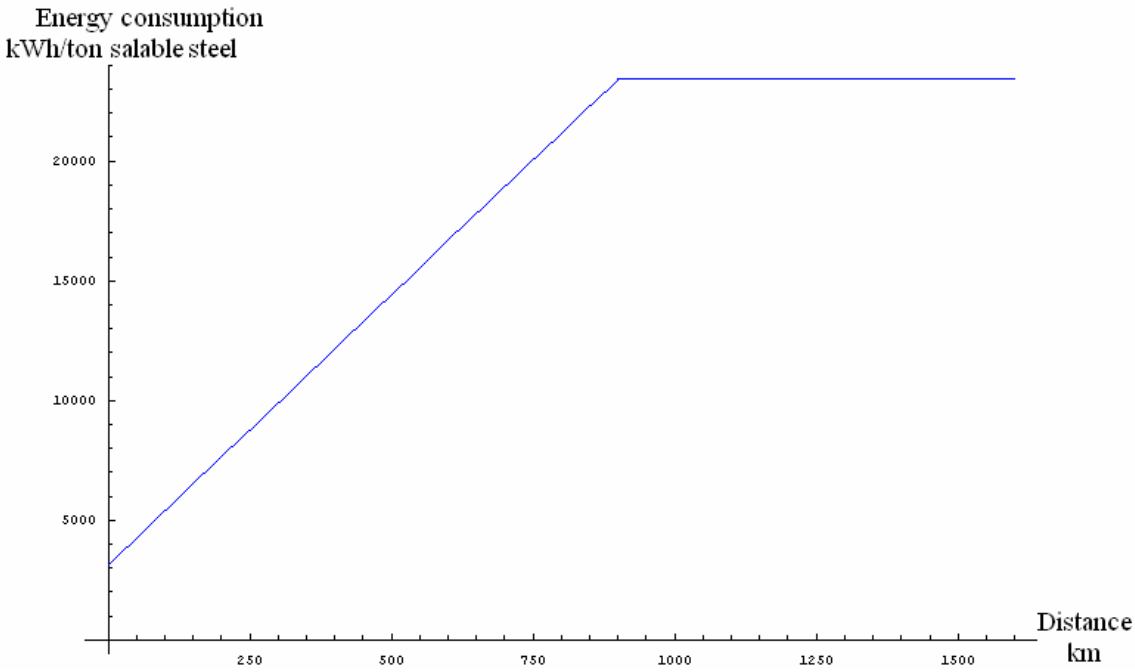


Figure 6-20 Steel recycling scenarios energy consumption

6.4.2.3 Disposal scenario

As mentioned in Section 6.1.1.2, the great lakes area is a large source of iron. In the disposal scenario, the steel is brought by train from Chicago to St Louis. Table 6.24 gives the itinerary of the supply phase and the vehicles used in each part of the travel. Figure 6.21 illustrates the itinerary from the mine to Chicago's train station.

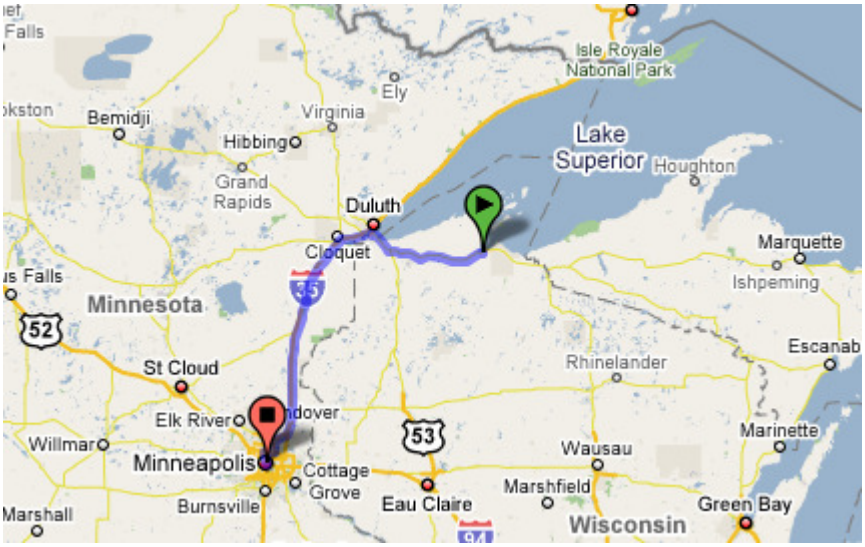


Figure 6-21 Distance between iron mine and Minneapolis train station (http://maps.google.com/)

Table 6-25 Steel DS transportation itinerary

Transportation order	Departure	Arrival	Transportation mode	Energy efficiency [kWh/ton-km]
1	Iron mine, WS	Minneapolis train station	Truck	0.18
2	Minneapolis train station	St Louis, train station	Train	0.06
3	St Louis, train station	St Louis, Plant	Truck	0.18

Table 6-26 Steel DS Distances and mass rate of transportation phase

Transportation order	Energy efficiency [kWh/ton-km]	Reusable mass rate	Distance [km]
1	0.18	0.8	450
2	0.06		900
3	0.18		50
TOTAL			1400

The energy consumption of steel disposal scenarios resulting is shown Figure 6.23.

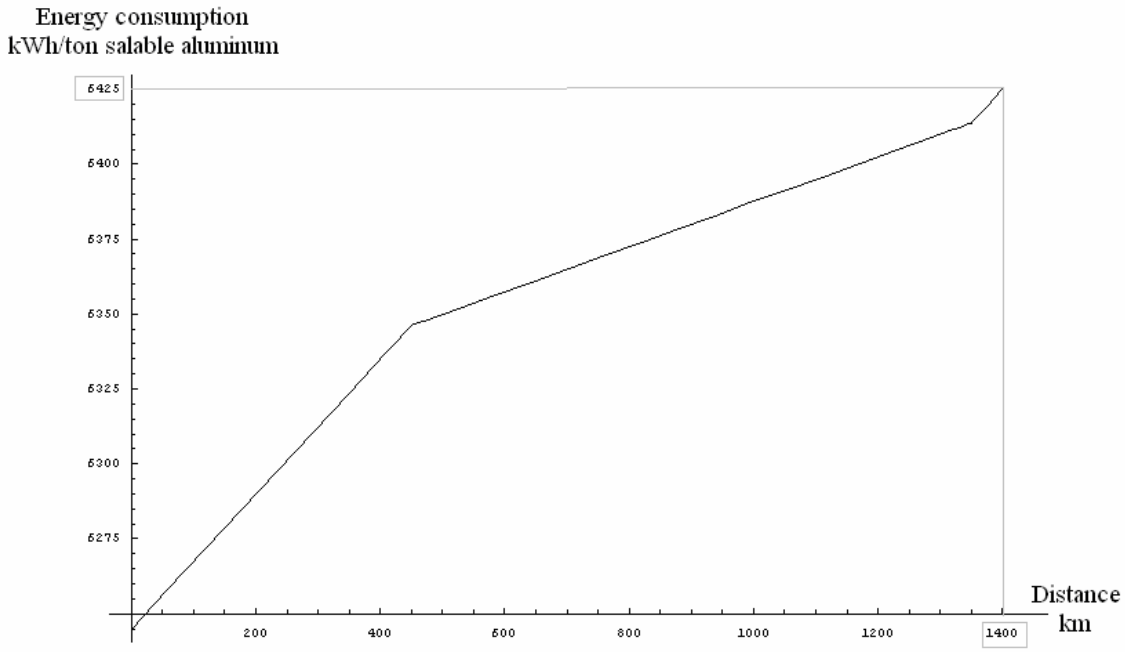


Figure 6-22Steel disposal scenarios energy consumption

In Figure 6.22, the slope changes at distances x = 450 km and x = 1350 km. These variations are due to the change of vehicles. At x = 450 km, train transportation substitutes truck transportation. Train efficiency is higher than truck. Therefore, the slope is smaller after 450 km. At x = 1350 km trucks are used again. The efficiency of truck transportation is lower than train efficiency. This result in an increased slope after 1650 km. The global energy consumption of steel disposal strategies corresponding to the itinerary given Table 6.26 is approximately 6425 kWh/ton salable steel.

6.4.2.4 Three scenarios energy consumption summary

Figure 6.23 is a superposition of the three scenarios functions. This graph shows the differences between energy consumptions.

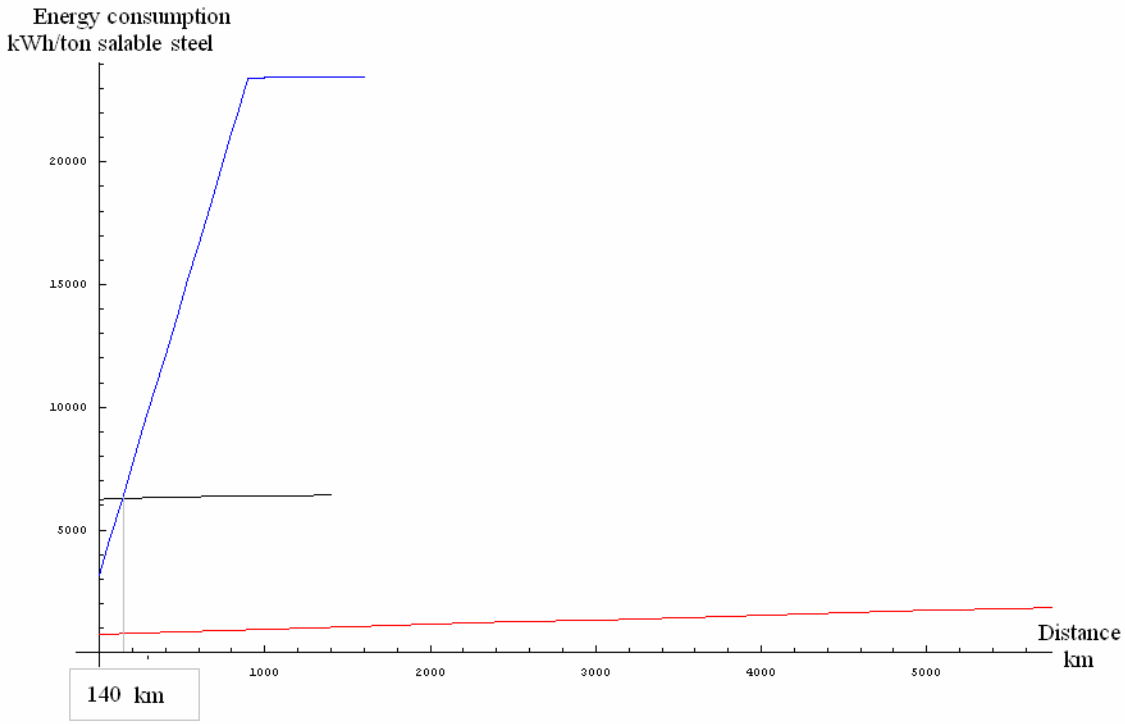


Figure 6-23 Steel scenarios energy consumption comparison

In this example, recycling scenarios energy consumption is higher than disposal scenarios after 180 km covered by transportation. Remanufacturing strategies energy consumption remains below recycling and disposal scenarios. In this situation, steel remanufacturing has a positive environmental impact from an energy consumption point of view. In the other hand, steel recycling scenarios have a negative impact from an energy consumption point of view. In order to keep the recycling energy consumption lower than disposal scenarios, the distance of collection at a rate of 0.008 should be lower than 140 km. Figure 6.24 is a superposition of the three scenarios energies where recycling scenarios steel municipal collection is performed by truck at a 0.008 steel mass rate, with a distance of 130 km. The collection with a rate of 0.77 is 865 km and the final transportation to TECH plant remains 600 km. The total distance covered is the same as in the previous steel recycling example.

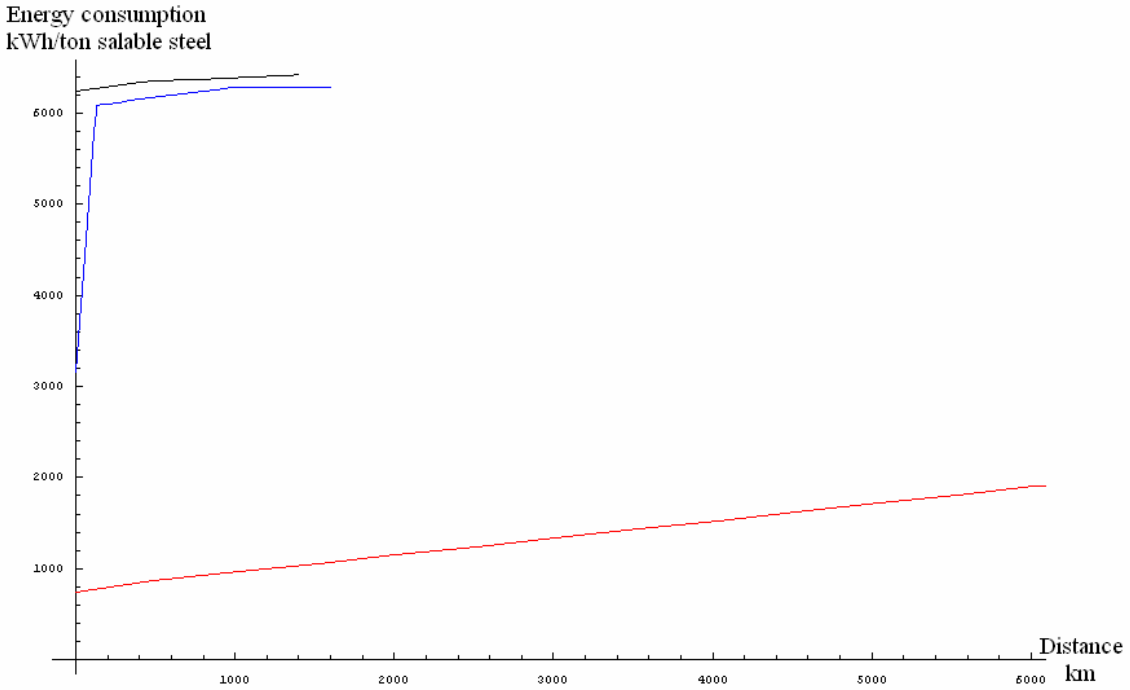


Figure 6-24 Example of better management of steel scenarios supply chain

In this configuration where recycling collection at a 0.008 reusable material mass rate is 130 km long, recycling scenarios are less energy consuming than disposal scenarios. Considering this last itinerary, remanufacturing scenarios have a positive impact from an energy point of view compared to recycling and disposal scenarios. Recycling scenarios have also a positive impact from an energy point of view compared to disposal scenarios.

6.4.3 Application closure

These examples showed that the relative environmental impact from an energy point of view depends mainly on the management of the supply chain. In fact, the impacts depend on the mass rate transported, the type of vehicle and the distances covered during transportation.

CHAPTER 7

ENERGY GENERATION AND TRANSPORTATION AIR EMISSIONS INVENTORY ANALYSIS

7.1 Air emissions analysis scope and goal

Academicians and governments have recognized the effects of certain gases and have classified them depending on their impact. Gases that have an influence on global warming are considered to be greenhouse gases. The emissions studied here that belong to this category are CO_2, CH_4 and N_2O. In order to estimate their global impact, they will be converted into *kg* $CO_{2\ equivalent}$ */ ton salable aluminum,* using the international standards given Table 7.1.

Table 7-1 Greenhouse emissions CO_2 equivalences

Category	Formula	Name	Category potential
Greenhouse gas	CO_2	Carbon dioxide	1
	CH_4	Methane	21
	N_2O	Nitrous oxide	310

These three gases are not the only greenhouse gases emissions, but these are our focus here because of their massive emissions caused by human activities. Other gases called "criteria pollutants" have an impact on environment but also on human health (Environmental Protection Agency 1998). They are defined by EPA as "air quality indicators". Six gases belong to this category: ozone (O_3), nitrogen dioxide (NO_2), sulfur

dioxide (SO_2), particulate Matter (PM), lead (Pb) and carbon monoxide (CO) (Environmental Protection Agency 1998). Ozone is not directly emitted into the air but results mainly from chemical reactions between NO_x and VOC with sunlight exposition. Evaluating O_3 here is susceptible to bring redundancy and uncertainty in the calculation given the exterior parameters such as light, temperature influencing the reactions. This is why O_3 will not be studied here. Particulate matters (PM) are made of dust, soot, smoke and all solid particles emitted in the air. They result also from condensation and transformations of SO_2 and VOC_s in the atmosphere. For these reasons, PM_s will not be taken in consideration here. Lead emissions have a direct impact on human health. Ingested or inhaled by air, lead causes serious central nervous system damages and heart diseases. To summarize, the criteria pollutants that will be focused here are: SO_2, NO_x, Pb and CO.

In addition to these two emissions categories, volatile Organic Compounds (VOC_s) and heavy metals such as mercury will be analyzed in this study (Environmental Protection Agency 1995). All emissions will be estimated in *g/ton salable aluminum* and *g/ton salable steel.* The emissions that will be studied here are summarized in Table 7.2. It should be noted that there exist ways to define further equivalence between gases. For instance SO_2 and NO_x participate to the acidification of rain and consequently lakes and soils. Their effect could be evaluated in function of the acidity (amount of H^+) they might produce. Nevertheless, given the numerous impacts of criteria pollutants and other compounds such as VOC_s or heavy metals, the conversion will be left to the reader.

Table 7-2 Studied emissions specification (EPA 2006)

	Chemicals definition	Name
Greenhouse gas	CO_2	Carbon dioxide
	CH_4	Methane
	N_2O	Nitrous oxide
Criterial pollutants	SO_2	Sulfure dioxide
	NOx	Nitrogen oxides

To conclude, liquid waste and solid waste are going to be studied. Estimating natural resources waste is indispensable to complete the evaluation of end-of-life strategies environmental impact. In a first time, it is necessary to define the boundaries of this waste study. The quantity of natural resources (coal, gas, fuel…) consumed by power generation will not be specified here. In fact, evaluating this resource would be redundant with the energy consumption evaluation. The amount of waste evaluated here will be considered without any recycling or cleaning issue. In fact, post treatments are responsible of supplementary pollutions and energy consumptions and depend on companies' strategies and environmental policies. This uncertainty parameter will be excluded from the current study.

7.2 Air emissions resulting from energy generation

Energy generation is responsible of high levels of air emissions. This section is dedicated to the analysis of the air emissions resulting directly from the energy necessary to each end-of-life strategies process.

7.2.1 Assumptions about power generation sources

The losses during transfer or extraction of the different fuel, especially natural gases, are not taken in consideration here. Some important assumptions about energy generations and studies boundaries have been made and need to be detailed.

7.2.1.1 Electricity

The oil, coal and gas CO_2 emissions are issued from EIA data base. In this case, given their heating role in the different scenarios, their combustion is assumed to be complete. Whereas electrical emissions are issued from US power plants statistical emissions over the past decade. As installations can be optimized to guaranty a complete combustion of the fuel, electricity is provided by independent companies and thus can not be assumed as ideal.

7.2.1.2 Diesel

In this study, Diesel and all other fuels combustion is assumed to be complete and enough long to neglect other polluting emissions such as CO, NO, etc… The combustion results exclusively to the emission of CO_2. In reality, the combustion occurring an engine is too rapid to be able to transform all CO emitted into CO_2 or NO into N_2 and H_2O and therefore emits small quantities of other pollutants than CO_2. This is not the case in a power plant where the reactions are slow and therefore complete. The complete combustion of fuel that is assumed and used in this study is given Equation 7.1

$$C_nH_k + (k/4+n)(O_2 + 3.76\,N_2) + S \Rightarrow nCO_2 + (k/2)H_2O + 3.76(k/4+n)N_2 + SO_2 \qquad [7.1]$$

The coefficients m and n are coefficients that depend on the molecule of fuel burnt. For instance in the case of methane (CH_4), n= 1 and k = 4. The molar mass of carbon M_c = 12g/Mol, the molar mass of M_h = 1 g/Mol and the molar mass of oxygen M_o= 16 g/Mol.

7.2.1.3 Heavy oil

Heavy oils are responsible of large emissions of SO_2 and NO_x linked to the high quantities of S and N contained in the heavy fuel. The emissions of SO_2 and NO_x are difficult to estimate. In fact, they depend on many parameters and surprisingly appear to be in some combustion configuration inversely proportional to the S or N content in the burnt fuel (Molero 1996). Therefore, the SO_2 and NO_x emissions will be issued from statistical emissions edited by EPA rather than calculation as often as possible. The emissions of CH_4 and N_2O will also be extracted from official statistics to guaranty the realism of the results (Energy Information Administration 2002).

7.2.1.4 Coal

As mentioned before, fuels combustions dedicated to the scenarios heating phases are assumed to be complete. Therefore pollutants such as heavy metal present in gas, oil and coal are entirely rejected in the air after combustion.

7.2.2 Air emissions resulting electricity generation

The US production of electricity uses mainly coal, nuclear and natural gas fuels. The proportions of air emissions emitted by the 4.055 Billion kWh produced by US power plants in 2005 are given Figure 1. It appears that 50 % of the electrical energy is generated by coal combustion, 19.5 % of nuclear power and 18.5 % of natural gas. The

rest is produced thanks to hydroelectric (6.5 %) and petroleum (3%) sources and renewable energies (2.5 %) (Schnapp 2006).

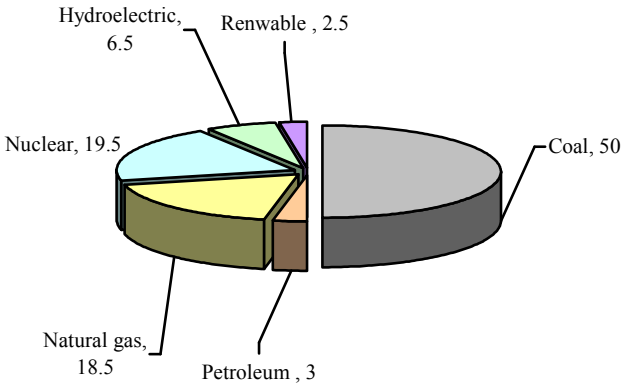


Figure 7-1 US energy generation primary fuels

Nuclear, renewable and hydroelectric energies do not emit any greenhouse gas, criteria pollutants or heavy metal. The nuclear polluting waste is excluded from this research (hazardous uranium waste and radioactive risks and effects are not part of the study). This section is dedicated to global air emissions of power plants. The results are therefore not issued by combustion emissions calculation but issued from data surveys on operating power plants performed by the US Energy Information Administration (EIA).

7.2.2.1 Greenhouse gas emissions

- CO_2 : A 2002 governmental survey (Energy Information Administration 2002) that collected emissions through all the states revealed that the average CO_2 emissions of US power plants is 0.606 g/kWh electricity generated. Another survey driven by EIA as well gives the CO_2 emissions from 1994 to 2005 and verifies the previous result (Schnapp

2006). Table 7.3 reports the necessary data of this survey from 2000 to 2005. The estimation resulting from this survey sample gives also an emission rate around 0.610kg/kWh electrical energy produced.

Table 7-3 Electrical energy generation air emissions (Energy Information Administration 2002)

Description	2005	2004	2003	2002	2001	2000
All energy sources [1000 MWh]	4,054,688	3,970,555	3,883,185	3,858,452	3,736,644	3,802,105
Emissions CO2 [1000 metric tons]	2,513,609	2,456,934	2,415,680	2,395,048	2,389,745	2,429,394
Emission rate CO2 [kg/kWh]	**0.6199266**	**0.6187886**	**0.6220873**	**0.6207277**	**0.6395431**	**0.6389603**

- CH_4: the 2002 governmental survey also determined the CH_4 quantities emitted by each US state from 1998 to 2000. The average emission of 0.005 g/kWh is considered here. The worse case reported is 0.026 g/kWh in Maine and the best case is 0.0014 g/kWh electricity generated in Oregon (Energy Information Administration 2002).
- N_2O: this mean average emission is evaluated by the same source as previously at 0.0087 g/kWh electricity generated. This value will be used here. The worse case is 0.015 g/kWh in North Dakota and the best case is 0.0014 g/kWh electricity generated in Idaho (Energy Information Administration 2002).

7.2.2.2 Criteria pollutants

- SO_2: The SO_2 emissions have been estimated the same way as for CO_2 emissions through a data collection from 1994 to 2004 (Schnapp 2006). A sample of this survey has been used here to evaluate SO_2 emissions resulting from US electricity generation. The

SO_2 emissions decrease every year. The 2005 and 2004 remain around 0.0025 kg/kWh energy produced.

Table 7-4 US electrical generation SO_2 emissions (Schnapp 2006)

Description	2005	2004	2003	2002	2001	2000
All energy sources [1000 MWh]	4,054,688	3,970,555	3,883,185	3,858,452	3,736,644	3,802,105
Emissions SO2 [1000 metric tons]	10,340	10,309	10,646	10,881	11,174	11,297
Emission rate SO2 [kg/kWh]	**0.00255**	**0.002596**	**0.002742**	**0.00282**	**0.00299**	**0.002971**

- NOx: The NOx production is also given by the same survey performed from 1994 to 2005. A 5 years sample is reported Table 7.5 and gives an estimation of US power generation NO_x emissions. The emissions decrease through the years. They remain around 0.001 kg/kWh energy produced (Schnapp 2006).

Table 7-5 US electrical generation NOx emissions (Schnapp 2006)

Description	2005	2004	2003	2002	2001	2000
All energy sources [1000 MWh]	4,054,688	3,970,555	3,883,185	3,858,452	3,736,644	3,802,105
Emissions NOx [1000 metric tons]	3,961	4,143	4,532	5,194	5,290	5,380
Emission rate NOx [kg/kWh]	**0.000977**	**0.001043**	**0.001167**	**0.001346**	**0.001416**	**0.001415**

7.2.3 Air emissions resulting from heat generation

Beside the electrical purpose, some materials are widely used in the industry for heating activities. Coal and natural gas are two principle fuels that are commonly used for this.

The applications in the end-of-life strategies will be discussed later in the chapter. The following emissions are calculated thanks to heating fuels chemical combustion and are verified by public governmental and academic data. For the following, carbon heating value is estimated at 14,500 BTU/lb and Sulfure heating value is estimated at 4,000 BTU/lb.

7.2.3.1 CO_2 emissions resulting from heat generation

CO_2 resulting from Coal combustion

Carbon is the main component in coal. This results in a high emission of CO_2 after combustion. Carbon present in coal is the principle source of heat in coal. The heating value of coal depends on its compositions. In Fact, there exist four types of coal differentiated by their composition. These are Anthracite, Bituminous, Sub-bituminous and Lignite. Their respective heat value is given Table 1.

Table 7-6 Coal types and characteristics

	% of Carbon in mass	Heating value [BTU/lb]	Use
Anthracite	86 to 98	15000	Home heating
Bituminous	45 to 86	10500 to 15000	Electricity and coke
Sub-bituminous	35 to 45	8300 to 13000	Low sulfur, cleaner burst
Lignite	25 to 35	4000 to 8300	Electircity

The heating value of coal is between 4,000 to 15,000 BTU/lbs. Nevertheless, the lignite coal is rarely exploited because of its low heat capacity. Therefore, the approximate value of 10,000 BTU/lb (6461 kWh/ton) will be assumed to be representative of coal's heating value. This heating value corresponds to a carbon content of approximately 50%.The

association of 1 molecule of carbon with two molecules of oxygen is determined Equation 7.2:

$C_s + 2\ O_g \rightarrow CO_{2\ gas}$ [7.2]

Thanks to stoechiometry, it is possible to determine the amount of CO_2 generated by the combustion of Carbon (Equation 7.3).

$$[C] = \frac{[O]}{2} = [CO_2] \quad [7.3]$$

$$\frac{mC}{MC} = \frac{mO}{2 \times MO} = \frac{mCO_2}{MCO_2}$$

$$m\ CO_2 = \frac{mC}{MC} \times MCO_2 = \frac{mC}{12} \times (2 \times 16 + 12) = 3.67 \times mC$$

$$\boxed{mCO_2 = 3.67\ mC}$$

Assuming a complete combustion, using Equation 7.3 result, the amount of CO_2 generated by coal combustion is determined Table 7.7.

Table 7-7 CO_2 emissions from coal

Coal	% of carbon in mass	CO2 emissions [kg/ton coal]	Heating value [kWh/ton coal]	CO2 emissions [kg/ kWh]
Anthracite	98	3596.6	9690	0.37
	86	3156.2	9690	0.32
Bituminous	86	3156.2	9690	0.32
	45	1651.5	6783	0.24
Sub-bituminous	45	1651.5	6783	0.24
	35	1284.5	5361.8	0.24
Lignite	35	1284.5	5361.8	0.24
	25	917.5	2584	0.35

The CO_2 emissions determined in Table 7.7 result from calculation. They are verified by the Energy Information Administration data base. Table 7.8 reports official coal emissions (Energy Information Administration 2006).

Table 7-8 Governmental Co2 emissions from coal combustion

	CO2 emissions			
Coal	lbs/ton	kg/ton	lbs/Millions BTU	g/kWh
Anthracite	4237.376	1919	227.4	341.1
Bituminous	5424.43	2457	205.3	307.95
Sub-Bituminous	4087.49	1851	212.7	319.05
Lignite	3070.76	1391	215.4	323.1

The CO_2 emitted by coal is around 300 g/kWh. This approximation is also verified by governmental data (D. Naranjo 2005), where Carbon dioxide emissions resulting from coal are estimated at 208,000 lbs/BTU (322 g/kWh).

CO_2 resulting from Natural gas combustion

Natural gas consists in a hydrocarbon gaseous mixture. It might contain up to 85% of methane (CH_4), about 10% of ethane (C_2H_6) and also traces of propane (C_3H_8), butane (C_4H_{10}), pentane (C_5H_{12}) and other alkanes. For the calculation, only the main component methane and ethane will be taken in consideration, the rest will be neglected. The approximation of a natural gas made of 90% of methane and 10 % of Ethane will be done in the study (Speight 2007). The heating values natural gas components are given Table 7.9 (www.EngineeringToolBox.com 2007) (Hydrogen energy hydrogen basics 2007).

Table 7-9 Natural gas components heating value

Natural gas	BTU/lbs	kWh/ton
Buthane	21640	13980
Ethane	22198	14440
Methane	23811	15382
Propane	21500	13889
Natural gas	19500 to 22500	12600 to 14535

Natural gas heating value $H_{natural\ gas}$ will be approximated in this study at 14,500 kWh/ton.

$$H_{natural\ gas} = 14{,}500 \text{ kWh/ton}$$

The CH_4 combustion formula is given Equation 7.4:

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O \qquad [7.4]$$

The stoechiometry gives the ration between methane mass combusted and CO_2 emitted.

$$[CH_4] = [CO_2] \qquad [7.5]$$

$$\frac{mCH_4}{MCH_4} = \frac{mCO_2}{MCO_2}$$

$$mCO_2 = \frac{mCH_4}{MCH_4} \times MCO_2$$

$$mCO_2 = \frac{44}{16} \times mCH_4$$

$$mCO_2 = 2.75 \times mCH_4$$

The Ethane (C_2H_6) combustion formula is given Equation 7.6:

$$C_2H_6 + 5\ O \rightarrow 2\ CO_2 + 3\ H_2O \qquad [7.6]$$

The stoechiometry results in the CO_2 emission given by Equation 7.7:

$$[C_2H_6] = \frac{[CO_2]}{2} \qquad [7.7]$$

$$\frac{mC_2H_6}{MC_2H_6} = \frac{mCO_2}{2MCO_2}$$

$$mCO_2 = \frac{2 \times mC_2H_6}{MC_2H_6} \times MCO_2$$

$$mCO_2 = \frac{2 \times 44}{30} \times mC_2H_6$$

$$\boxed{mCO_2 = 2.9 \times mC_2H_6}$$

Given the assumption that natural gas is composed by 90% of Methane and 10% of ethane, the CO_2 emitted by one metric ton of gas combustion is given by Equation 7.8:

$$m_3CO2 = 0.9 \times 2.75 + 0.1 \times 2.9 = 2.76 \text{ ton} \quad [7.8]$$

Given the heating values given Table 7.9, the emission rate of CO_2 Rco_2 resulting from the combustion of natural gas is given by Equation 7.9:

$$Rco_2 = \frac{m_3CO2}{H_{\text{natural gas}}} = \frac{2.76}{14500} = 0.000190 \text{ ton/kWh} = 190 \text{g/kWh} \quad [7.9]$$

$$\boxed{Rco_2 = 190 \text{ g/kWh}}$$

This CO_2 emission rate is verified by governmental data. In fact, the Energy Information Administration gives a rate of 117080 lbs/ BTU CO_2, which is 181 g/kWh CO_2 (Energy Information Administration 2006).

7.2.3.2 CH_4 emissions resulting from heat generation

<u>CH_4 resulting from Coal combustion</u>

Coal at a primary state, in mines, have high levels of CH_4. This gas results from the "coalification" of underground vegetation relics that did not go through the usual surface

breakdown. This gas at a concentration of 5% to 15% is explosive and therefore dangerous for the extraction and the workers. Therefore, mines constantly vaporize the CH_4 in the atmosphere upon harmless concentration of 1% of coal mass. The mining emissions of energy resources are out of the boundary of the study. Therefore, the CH_4 considered in this study is the 1% remaining in the coal after degasification (Williams 1999). Therefore, the CH_4 emission rate of coal is:

$$mCH_4 = \frac{1}{100} \times mCoal$$

R' CH_4 = 10 kg/ton

$$RCH_4 = \frac{R'CH_4}{HCoal} = \frac{10}{6461} = 0.00154 kg/kWh = 1.54 g/kWh \quad [7.10]$$

CH_4 resulting from natural gas combustion

Combustion of gas for heating is assumed to be complete. The potential leaks and accidental emissions of CH_4 due to maintenance and combustions efficiencies are not taken in consideration in this study. The emissions of CH4 from natural gas combustion are 0 g/kWh.

7.2.3.3 N_2O emissions resulting from heat generation

N_2O resulting from Coal combustion

A report issued from Corobrik Lawley corporation measured the greenhouse gas emitted by coal and natural gas combustion during one year (Corobrik Lawley Inc 2005). The mean average of N_2O emissions in 2005 is reported as 362.9 kg for a total energy generated by coal of 252,811 GJ. The correspondent NOx emission rate is given by Equation 7.9.

252811 GJ = 70 225 277.8 kWh

$$R_{coal}\ N_2O = \frac{362900}{70225278} = 0.00517 g/kWh \quad [7.11]$$

R N_2O = 0.00517 g/kWh

N_2O resulting from natural gas combustion

The Corobrik Lawley data survey also reports the emissions of Natural gas combustion (Corobrik Lawley Inc 2005). The 2005 emissions of N_2O were 773 kg. They resulted from the energy generation of 336,096 GJ from Natural gas. Equation 7.11 gives the resulting N_2O emission ratio.

336,096 GJ = 93,360,000 kWh

$$R_{gas}\ N_2O = \frac{773000}{93360000} = 0.00828 g/kWh \quad [7.12]$$

7.2.3.4 N_2O emissions resulting from heat generation

SO_2 resulting from coal combustion

The sulfur dioxide (SO_2) emissions resulting from coal combustion depend on the Sulfur content of coal. The Sulfure present in coal has two different forms: the pyrite and the organic sulfur. The first one has a different density than coal and might be removed easily with washing processes. The second one can not be removed before combustion. Nevertheless, in this study, supplementary treatments such as gas removing are not part of the boundaries (Davis 2001) (Chou 2001). This is why the emissions resulting from gas will be calculated in function of the initial sulfur content of coal, which encloses pyrite and organic Sulfur. SO_2 coal emissions result exclusively from the sulfur present in coal (Environmental Protection Agency 2005). A survey in Illinois coal mines determined a ratio $R_{Pyrite/Org}$ of Pyrite and organic sulfure between 0.18 and 6.5 (Shilts 2006).

$$0.18 < R_{Pyrite/Org} = \frac{mPyrite}{mOrganicsulfur} < 6.5 \quad [7.13]$$

In a survey over Illinois State, pyritic sulfur is evaluated to be originally 3.4% of call mass. The organic sulfur mass content is evaluated around 2.2% of coal (Anderson 1996).

$$m\ SO_2 = \frac{3.4}{100} + \frac{2.2}{100} = \frac{5.6}{100} \times mCoal \quad [7.14]$$

$R_{coal}\ SO_2 = 0.056$ ton/ton coal = 56 kg/ton coal

$$R_{coal}\ SO_2 = \frac{56}{6461} = 0.0087 kg/kWh = 8.7 \text{ g/kWh}$$

SO_2 emissions resulting from coal is 8.7 g/kWh. This value is much higher than results given from environmental surveys and administrations. In fact, the Energy Information Administration (EIA) estimates coal SO_2 emissions from electric power generation between 0.84 and 1.74 g/kWh. Some pretreatments of coal that are not taken in consideration here might have occurred. Another regulation called the Clean Air Interstate Rule (CAIR) reports coal emissions varying between 0.1lbs/MM BTU (0.15 g/kWh) with Sulfure removing catalyses and 5 lbs/MM BTU (7.7 g/kWh) without any control for high Sulfur coal (Environmental Protection Agency 2005). This last result is coherent with the $R_{coal}\ SO_2 = 8.7$ g/kWh resulting from the previous calculation Equation 12.

<u>SO_2 resulting from Natural gas combustion</u>

Natural gas used for boilers and coming from pipelines has usually very low content of sulfur. This study will not take in consideration the potential addition of sulfur for its warning smell in case of leak. The natural gas will be considered in its original composition. Therefore, the SO_2 emissions resulting from natural gas will be neglected.

This decision is confirmed by governmental data that give an emission of 0.0015 g/kWh (1 lb SO_2 / Billion BTU) (Environmental Protection Agency 2005) .

7.2.3.5 NOx

NO_x resulting from Coal combustion

Unlike SO_2 coal emissions that result exclusively from sulfur content in coal, NOx emissions result form Nitrogen present in coal and also in the air. A calculation of NOx emissions via calculation is inappropriate here. Consequently the NOx emissions of coal combustion will be inspired from governmental data resource. The CAIR analysis reports a coal NOx emission of 0.05 lbs/MMBTU which corresponds to 0.077 g/kWh in the case of controlled emissions to 1 lbs/MMBTU in an uncontrolled plant which is 1.55 g/kWh.

NO_x resulting from Natural gas combustion

Natural gas NOx emissions are determined by the CAIT analysis to be between 0.01 lbs/MMBTU (0.015 g/kWh) in the case of controlled emissions to 0.5 lbs/MMBTU (0.77 g/kWh) in the case of uncontrolled emissions (Environmental Protection Agency 2005).

Table 7-10 Power generation air emissions summary

	Greenhouse gas [g/kWh]			Criteria pollutants [g/kWh]	
Power	CO2	CH4	N2O	SO2	NOx
Electricity	610	0.005	0.0087	2.5	1
Coal	300	1.54	0.0052	7.7	1.55
Methane	190	0	0.008	0	0.77

7.3 Summary of air emissions resulting from scenarios processes energy consumption

The energy consumption resulting from energy consumption of each scenario processes are summarized Table 7.11 and Table 7.12. They have been calculated with the emissions rates of Table 7.10 and energy consumptions given Table 5.40 and Table 5.41.

Table 7-11 Aluminum transfer case air emissions resulting from energy consumption

Aluminum transfer case [ton emission/ton aluminum]					
	CO2	CH4	N2O	SO2	NOx
DS	12.9	0.01	0.0002	0.09	0.03
RCS	2.07	0.00001	0.00003	0.007	0.004
RMS	1.56	0.00001	0.00002	0.006	0.002

Table 7-12 Steel gears air emissions resulting from energy consumption

Steel gears [ton emission/ton steel]					
	CO2	CH4	N2O	SO2	NOx
DS	2.6	0.004	0.00004	0.03	0.007
RCS	1.7	0.00001	0.0002	0.007	0.003
RMS	0.45	0.000003	0.000006	0.002	0.0007

7.4 Air emissions resulting from transportation

Gas studied here are CO_2, CH_4 and N_2O. Most of the results have been defined thanks governmental surveys and governmental sources. They are mostly averages based on a regular data collecting and US governmental regulation. One action of the US Environmental Agency (EPA) is to limit air emissions resulting from transportation. Thus, these regulations will be used in this session to quantify freight vehicles. Nevertheless, regulations evolve with techniques through the years. This is why 5 Tiers

have been defined to represent 5 different regulations periods. They apply on the year of manufacture of the product. Given the fact that the vehicles running today have been manufactured in different years, it is important to know the regulation applied in this specific period:

- Tier 0. Are subjected to Tier 0 all vehicles manufactured on, or after, January 1, 1973, and before January 1, 2002; and upgraded vehicles manufactured prior to January 1, 1973. The standards apply when such a vehicle is manufactured, remanufactured, or imported on or after January 1, 2002.

Some exceptions exist to this rule; nevertheless it would not be interesting to go in such detail given the nature of the research.

- Tier 1. Vehicles manufactured on, or after, January 1, 2002, and before January 1, 2005 are subject to the Tier 1.
- Tier 2. Vehicles manufactured on, or after, January 1, 2005 are subject to the Tier 2.
- Tier 3. Vehicles manufactured on, or after, January 1, 2006 to January 2008 are subject to the Tier 3.
- Tier 4. Vehicles manufactured on, or after, January 1, 2008 to January 2015 are subject to the Tier 4.

Even if the year of the study is 2007, the vehicles on and off road are generally older than one year. This is why Tier 1 and Tier 2 regulations will be focused when dramatic regulations changes appear between the different periods[ex: NO_x].

7.4.1 Trucks air emissions

- CO_2: Trucks CO_2 emissions have been taken from governmental sources (EPA 2001) and verified by calculating the amount of CO_2 emitted by the combustion of one mole of diesel [$C_{12}H_{16}$]. Given Equation 7.1, the mass of CO_2 resulting from the combustion of Diesel is 3.3 times the mass of fuel burnt.

$$m\,C0_2 = 3.3 \times m\,C_{12}H_{16} \quad [7.15]$$

- Given the 0.265 L/km that is 0.22 kg/km Diesel consumption of a category I truck, the corresponding CO_2 emission is 0.726 kg/vehicle-km.
- Given the 0.33 L/km that is 0.27 kg/km Diesel consumption of a category II truck, the corresponding CO_2 emission is 0.891 kg/vehicle-km.
- Given the 0.5 L/km that is 0.416 kg/km Diesel consumption of a 30tons truck, the corresponding CO_2 emission is 1.37 kg/vehicle-km.

The CH_4 and N_2O are given for all three size categories of trucks. They are considered as averages values applicable to all three types of trucks.

- CH_4: The emission is issued from a governmental document (Davis 2006). They are reported in Table 13. The emissions displayed depend on the technology of the control applied to the trucks. Given this uncertain parameter, the control technology is assumed to be “moderate”. Thus the CH_4 emission assumed for a Diesel Heavy truck is 0.05g/vehicle-km as reported Table14.
- N_2O: This information is issued from a governmental document (Davis 2006).As for CH_4 emissions, the technology control for trucks is assumed to be “moderate”. Nevertheless. This detail is not significant given the same amount of N_2O for all types of

controls displayed in Table13. The N_20 emission for a HDDV is 0.03g/vehicle-km as reported Table 7.13.

Table 7-13 Trucks emission factors for CH4 and N2O HDDV IPCC/UNEP/OECD/IEA(1997), EPA 1998

Vehicle type	Control technology	N20	CH4	N20	CH4
		g/mi	g/mi	g/km	g/km
[Diesel]HDDV	Advanced	0.0483	0.0644	0.03	0.04
	Moderate	0.0484	0.0805	0.03	0.05
	Uncontrolled	0.0485	0.0966	0.03	0.06

- NO_x: Nitrogen oxides emissions have been gradually regulated and controlled since 1984 (EPA 2006). In 1998, the maximum emission of trucks was 4 g/vehicle-bhp-hr and in 2004, the regulation decreased the tolerance down to 2g/bhp-hr. In 2007, the EPA standard will be 0.2 g/vehicle-bhp-hr. Given the fact that these emissions standards apply to the year of production of the vehicles, most of the trucks driving on the road are older than 1 year. Thus, the 2004 regulation will be taken in consideration and applied to all trucks currently circulating. Thus, the maximum NO_x emission will be 2 g/vehicle-bhp-hr. The conversion used here corresponds 1996 diesel engines conversion factors determined by a governmental source (Environmental Protection Agency 1998).

  - For category I trucks (equivalent to EPA class 2B), the conversion factor is 1.09 bhp-hr/mi and the resulting NO_x emission is 2.18 g/vehicle-mi which corresponds to 1.35 g/vehicle-km.
  - For category II trucks (equivalent to EPA class 3 to class 6), the conversion factor is 1.55 bhp-hr/mi (mean average of class 3 to class 6 factors) and the resulting NO_x emission is 3.1 g/vehicle-mi which corresponds to 1.9 g/vehicle-km.

➢ For category III truck (equivalent to EPA class 7 to class 8B), the conversion factor is 2.7 bhp-hr/mi (mean average of class 3 to class 6 factors) and the resulting NO_x emission is 5.4 g/vehicle-mi which corresponds to 3.55 g/vehicle-km.

Table 7.14 summarizes the three categories of trucks greenhouse gas and criteria pollutants emissions.

Table 7-14 Greenhouse gas emission by size of truck

Category [kg]	mile/gallon	L/km	BTU/mile	kWh/km	emissions g/vehicle-km			
Truck	Consumption /vehicle		Energy/vehicle		CO2	N2O	CH4	Nox [2004]
I	9	0.265	16200	2.95	726	0.03	0.05	1.35
II	7.1	0.33	20318	3.7	891			1.9
III	4.7	0.5	31136	5.67	1370			3.5

7.4.2 Train air emissions

• CO_2: Given the fact that trains mainly consume diesel fuel [$C_{12}H_{16}$], the CO_2 emission has been calculated as previously. In reference to Table 6.10, train consume 18.1 L fuel/locomotive-km. This is equivalent to 15 kg/locomotive-km diesel consumption. The mass of CO_2 resulting from the combustion of Diesel is 3.3 times the mass of fuel burnt (Equation 7.15). This results in a 49.5 kg/locomotive-km CO_2 emission. Given the fact that a locomotive can transport up to 3200 tons which is equivalent to 106 wagons of 30 tons each, the emission for a 30 tons wagon is 0.464 kg/30 tons-km. These emissions are summarized Table 7.16.

Table 7-15 Train emissions for N2O and CH4 (IPCC/UNEP/OECD/IEA(1997))

Vehicle type	Control technology	N20	CH4	N20	CH4
		g/kg fuel		g/L	
Locomotives	Heavy oil/residual	0.08	0.250	0.054	0.22
	Diesel	0.08	0.250	0.05	0.2

- CH_4: as shown Table 7.5, the CH_4 emissions of a locomotive are estimated at 0.2 g/L of diesel consumed. This corresponds to 3.6 g/locomotive-km (considering 18.1 L/km fuel consumption [Table 6.10]). This results in 0.034 g/30tons-km (Davis 2006). These data are reported in the summarizing Table 7.16.

- N_2O: The emission is given table 7.15 (Davis 2006).The N_2O emission of a locomotive at 0.05 g/L of diesel consumed that is 0.9 g/locomotive-km (Considering 18.1 J/km fuel consumption [Table 6.10]). For a 30 tons container carried by train, given the consumption of 0.18L/30tons-km, the emission is 0.0084 g/30tons-km N_2O as reported Table 5.16.

- NO_x :The Tier 2 emission standard, comparable to 2004 truck NO_x regulation is 5.5 g/ bhp-hr that is 7.4 g/ kWh NO_x emission for a locomotive engine (EPA 1998) (Environment Canada 2004). Thus, given an energy consumption rate of 192 kWh/ton-km (Table 6.10), the emission of Nitrogen oxides is 1421 g/locomotive-km which corresponds to 13.3 g/30tons-km.

- SO_2: sulphur dioxide emission has been estimated by evaluating the amount of sulphur in one Liter of diesel. It is assumed that all the sulphur present in the fuel is transformed during the combustion into SO_2. Thus, the emissions depend on the type of fuel used and the current legislation. The sulphur emission does not depend on the year of the vehicle's engine fabrication as for NO_x but of the fuel used by the vehicle. Regulation about sulphur content in diesel fuel for off road vehicle appeared recently (Dieselnet

1997). In fact, before June 2007, the amount of sulphur in non-road diesel was not limited by environmental regulations. Thus the industrial specification was about 3000 ppm. The new regulation will be effective in June 2007 and will limit the amount of sulphur in non-road diesel to be 500 ppm [500 mg/kg diesel]. Given the density of diesel 0.833 kg/L, the sulphur concentration is evaluated at 416mg/L. Considering a fuel consumption of 18.1 L/locomotive-km, this results in 7.5 g/locomotive-km which gives 0.070 g/30tons-km. All greenhouse gas emissions and Criteria pollutants are summarized in table 7.16.

Table 7-16 Train energy consumption and gas emissions

		Consumption		Energy		CO2	N20	CH4	Nox	S2O
		Miles/gallon	L/km	BTU/mile	kWh/km	Emissions g/km				
Train	Locomotive	0.13	18.1	1,107,143	192	49,500	0.9	3.6	1421	7.5
	30 tons container	13.8	0.17	10,445	1.8	464	0.008	0.03	13.4	0.07

7.4.3 Ship air emissions

- CO_2: As shown Chapter 6, section 6.2.1, ship fuel is composed of 30% of diesel and 70% of residual fuel. Residual fuel and diesel are estimated to have the same content of carbon. Therefore the calculation will be done with a global emission rate of 161.386 lbs/MMBTU (250 g/kWh) (Energy Information Administration 2007). Given the ship fuel consumption of 1125 kWh/km, the CO_2 emission of a ship is given Equation 7.15.

$$R'_{ship}\,CO_2 = 250 \times 1225 = 281{,}250 \text{ g/vessel- km} \qquad [7.15]$$

$$R_{30container}\,CO_2 = 250 \times 1125 \times \frac{30}{25000} = 337.5 \text{ g/30 tons- km}$$

A study performed for the California Air Resources Board and the California Environment Protection Agency measured CO_2 emissions of two types of ships. This

study compares field measurements and literature data. The emission inventory has been realized on two different vessels. The first one is a container vessel, the "Sine Maerk" and the second is the "New spirit". They weight 26562 gross metric tons, which is coherent to the assumption of 25 000 tons cargo made in the current ship study. In this research, the CO_2 emissions reported from four different sources vary between 580 g/kWh and 660 g/kWh. These rates higher than the previous CO_2 emissions value (250 g/kWh). Another governmental source gives an exhaust emission from shipping of 56,000 ppm CO_2 (EPA 2001), which is 509 g/kWh considering a main heating value of Diesel and Residual fuel of 11 kWh/L (Table 6.8). This conversion is given Equation 7.16.

Exhaust concentration = 56 000 ppm $\approx$ 56 000 mg/L fuel

$$= \frac{56000}{11} = 5090 mg/kWh = 509 g/kWh \quad [7.16]$$

Considering these results, CO_2 emissions from freight ships will be approximated to 550 g/kWh. Given the 1125 kWh/vessel-km consumed by 25000 metric tons, the CO_2 emissions resulting for 30 tons container is given by Equation 7.17.

$$R_{30\text{ tons ship}}\,CO_2 = \frac{550 \times 1125 \times 30}{25000} = 742.5 \text{ g/30 tons-km} \quad [7.17]$$

$$\boxed{R_{30\text{tons ship}}\,CO_2 = 742.5 \text{ g/30tons-km}}$$

- CH_4: the emissions are given Table 7.17 (Davis 2006). The CH_4 emission of a ship is estimated at 0.2 g/vessel-L of diesel consumed or 19.7 g/vessel-km that corresponds to 0.024 g/30tons-km CH_4 emission (considering 98.5 L/km fuel consumption *Table 6.11*).

- N_2O: the emissions are showed Table 7.17 (Davis 2006). The N_2O emission of a ship is estimated at 0.07 g/vessel-L that is 6.9 g/vessel-km (considering 98.5 L/km fuel consumption [Table 6.11]). For a 30 tons container carried by boat, the emission is equivalent to 0.0083 g/30 tons-km.

Table 7-17 Ship emission factors for CH4 and N2O

Vehicle type	Control technology	N20	CH4	N20	CH4
		g/kg fuel		g/L	
Ship and boats	Residual	0.08	0.230	0.07	0.2
	Distillate	0.08	0.230	0.07	0.2
	Gasoline	0.08	0.230	0.07	0.2

- NO_x: NO_x regulation admits emissions from 9.8 g/ bhp-hr to 17 g/ bhp-hr for ship depending on their power and their displacement. The ship that are studied here are freight ships. The average of a cargo power is estimated to be 4500 bhp (6032 kW) (Network: 2006).Thus given the emissions standard given Table 7.18, the NOx emission will be assumed to be 9.8 g/vessel-kWh that is 11025 g/vessel/km and 13.2 g/30tons-km. (Federal highway administration 2007)

Table 7-18 Marine vessel emission EPA standard (US Department of Transportation 2006)

Engine category	Power	Displacement	Year	HC+Nox	PM	CO
Category 1	kW>37	L/cy<0.9	2005	7.5	0.4	5
		0.9<L/cy<5.0	2004-2007	7.2	0.3-0.2	5
Category 2	All cat 2		2004-2006	IMO stds		
	kW> 3300	15 <L/cy<25	2007	9.8	0.5	5
		25<L/cy<30	2007	11	0.5	5
Category 3		L/cy>30	2004	IMO stds		
IMO STDS	If rpm>2000			Nox = 9.8 g/kwh		
	If 130 < rpm< 2000			45*rpm^-0.2 g/kWh		
	If rpm <130			17 g/kwh		

- SO_2: as in the train case, Sulphur dioxide emission has been estimated by evaluating the amount of sulphur in one Liter of diesel. It is also assumed that all the sulphur present in the fuel is transformed during the combustion into SO_2. The diesel fuel used in maritime transportation is submitted to the same regulations as in rail transportation. Nevertheless, given the large amount of heavy oil used by a ship (70%), the sulphur emission is much more important than for trains. Heavy oil contains from 15 000 to 50 000ppm of sulphur. The US Environmental Protection Agency (EPA) estimates the worldwide average marine Sulfure oil level at 27,000 ppm (27 000 mg/kg fuel). (Dieselnet 1997). Marine vessels fuel is composed by 30% of diesel and 70 % of heavy oil. Therefore, 30% diesel will product 500ppm ($500 \times 0.833 = 416.5 mg/L$) of SO2 and 70% heavy oil will produce 38,400ppm ($38400 \times 0.900 = 34560 mg/L$). This leads to a global emission of 27,000ppm ($0.3 \times 416.5 + 0.7 \times 34560 = 24\ 317$ mg/L). These 24,317mg/L result in a SO_2 emission of 2,395 g/vessel-km and 2.9g/30tons-km. All the greenhouse gas and criteria pollutants defined previously are summarized in Table 7.19.

Table 7-19 Ship energy consumption and gas emission

	miles/gallon	L/km	BTU/mile	kWh/km	g/km				
Ship	Consumption		Energy		CO2	N20	CH4	Nox	S2O
Vehicle	0.02	98.5	6,325,000	1125	618,750	6.9	19.7	11025	2395
30 tons container	19.6	0.12	7590	1.35	18562	0.0084	0.024	13.2	2.9

7.5 Air emissions resulting from transportation summary and processes energy consumption summary

Table 7.20 gives the summary of energy consumption of transportation and the related air emissions.

Table 7-20 transportation energy consumption and related air emissions

		Miles/gallon	L/km	BTU/mile	kWh/km	Emissions g/km				
		Consumption		Energy		CO2	N20	CH4	Nox	S2O
Truck	30 tons vehicle	4.7	0.5	31100	5.3	1370	0.03	0.05	3.5	
Train	Locomotive	0.13	18.1	1,107,143	192	49,500	0.9	3.6	1421	7.5
	30 tons container	13.8	0.17	10,445	1.8	464	0.008	0.034	13.4	0.07
Ship	vessel	0.02	98.5	6,325,000	1125	618,750	6.9	19.7	11025	2395
	30 tons container	19.6	0.12	7590	1.35	18562	0.0084	0.024	13.2	2.9

Table 7.21 gives a summary the air emissions resulting from scenarios processes. These emissions are given in $CO_{2\ \text{equivalent}}$ for greenhouse gases. The criteria pollutants have not been converted into other units.

Table 7-21 Air emissions resulting from aluminum processes energy consumption

END OF LIFE STRATEGIES	PARAMETERS	PROCESS															
		2,1			2,2			3,1			4,1			4,2			
DISPOSAL STRATEGY	PROCESS	Alumina refining			Electrolysis			XXX			Transfer case casting			Transfer case machining			
	TYPE OF FUEL	50 % Gas+ 50 % coal +			Electricity			N/A			Electricity			Electricity			
	EMISSION TYPES	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	N/A			CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	
	[g/ton Aluminum]	3685024	53900	16240	9556125	37500	15000				273942,3	1075	430	12741,5	50	20	
RECYCLING STRATEGY	PROCESS	Sorting			XXX			Ingot melting			Transfer case casting			Transfer case machining			
	TYPE OF FUEL	Electricity			N/A			Gas			Electricity			Electricity			
	EMISSION TYPES	CO2 eq	SO2	Nox				CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	
	[g/ton Aluminum]	1627727	6387,5	2555	N/A			230976	0	924	273942,3	1075	430	12741,5	50	20	
REMAN. STRATEGY	PROCESS	Sorting			Cleaning			XXX			XXX			Transfer case remachining			
	TYPE OF FUEL	Electricity			Electricity			N/A			N/A			Electricity			
	EMISSION TYPES	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	N/A			N/A			CO2 eq	SO2	Nox	
	[g/ton Aluminum]	1627727	6387,5	2555	24209	95	38							2548,3	10	4	

Table 7-22 Air emissions resulting from steel processes energy consumption

END OF LIFE STRATEGIES	PARAMETERS	STEEL PROCESSES																		
		2,1			2,2			2,3			3,1			4,1			4,2		
DISPOSAL STRATEGY	PROCESS	Sinter making			Iron pig making			steel making			XXX			Cylinder casting			Steel gear Machinng		
	TYPE OF FUEL	77% Coke 3% Gas 20% Elec			10% Gas 20% Other (Coal, El., oxy…)			1/3 Electricity 1/3 other (coal, gas…)			N/A			Electricity			Electricity		
	EMISSION TYPES	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	N/A			CO2 eq	SO2	Nox	CO2 eq	SO2	Nox
	[g/ton steel]	52695	25716	191	1521718	23560	5448	66893	875	105				1070286	4200	1680	31854	125	50
RECY STRATEGY	PROCESS	Sorting			XXX			XXX			Steel melting			Cylinder casting			Steel gear Machinng		
	TYPE OF FUEL	Electricity			N/A			N/A			60% Electricity 40% Other (Oxygen, graphite, gas…)			Electricity			Electricity		
	EMISSION TYPES	CO2 eq	SO2	Nox	N/A			N/A			CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox
	[g/ton steel]	465065	1825	750							420	1050	420	1070286	4200	1680	31854	125	50
REMAN. STRATEGY	PROCESS	Sorting			Cleaning			XXX						XXX			Steel gear remachinng		
	TYPE OF FUEL	Electricity			Electricity			N/A			N/A			N/A			Electricity		
	EMISSION TYPES	CO2 eq	SO2	Nox	CO2 eq	SO2	Nox	N/A			N/A			N/A			CO2 eq	SO2	Nox
	[g/ton steel]	465065	1825	750	2548	10	4										5097	20	50

CHAPTER 8

END-OF-LIFE STRATEGIES PROCESSES AIR EMISSIONS AND NATURAL RESOURCES WASTE

8.1 Phase 1: Material supply

8.1.1 DS phase 1, emissions and wastes resulting from process

8.1.1.1 Aluminum transfer case

Bauxite mining

Air emissions

Bauxite ore is usually close to the surface. Therefore, Bauxite mines are often open to the air. This results in destruction of all vegetation and wildlife present on the mining field. Of all world bauxite mined lands, 76% appears to be forest. Trees consume CO_2 during the day and participate actively to the decrease of CO_2 in the atmosphere. Consequently, the destruction of vegetation results in the increase of CO_2 in the atmosphere. This CO_2 not consumed by the destroyed forest will be considered as CO_2 emissions from the mining process.

Solid waste

The impoverishment of the mines environment is linked to the high amount of land waste. Bauxite has a low conversion rate when it is converted into alumina. In fact, 2 kg Bauxite are necessary to create 1 kg of Alumina. The waste of material resulting from alumina production is called red mud. Given the fact that alumina production plants are

often far away from the extraction site, red mud is hardly reused into land reconstruction and results in a high amount of waste. Given the fact that 1 kg waste are rejected per kg Alumina produced and that 2 kg Alumina are necessary to create 1 kg of aluminum, the solid waste on a mining site is equal to **2 tons/ton salable aluminum.**

8.1.1.2 Steel gears

Iron ore mining

Solid waste

"Iron is the 4th most abundant rock-forming element on the earth and composes about 5% of the earth crust" (USCG minerals 1998). Most of the iron ore (98 %) shipped is used in the iron and steel industry. Brazil had been for years one of the leader of iron ore. However, US is capable of producing its own iron ore. In fact 80 % to 90% of the overall US iron ore consumption was supplied by US mines, mostly located around the great lakes in Minnesota and Michigan (USGS minerals 1998) (Jorgenson 2007). US iron ore (Taconite) has a general iron content of 20% to 30%, which implies high amounts of wastes responsible of ecological disorders on the mining sites (Jorgenson 2007) (ENVIS Goa Centre 2005).

Given the fact that primary iron ore has 20 to 30% of iron content and given the fact that pellets (mine outputs) have a content of 60 to 70 % iron, the consequential waste is estimated at 40 % Wt of pellets. The US department of the interior evaluated the iron mines waste at 45% wt of the total extraction. Therefore, the solid waste of iron mining will be estimated in this study at 45 kg/100 kg ore extracted. Figure 8.1 gives the composition of US steel material primary resource. For this particular waste estimation, Pellets will be assumed to be the only source of Iron ore (sinter and Iron ore will be

neglected). With the assumption of 45% wt waste in the mining landfills, 1 ton of pellets production corresponds to 0.8 tons of waste. Given the fact that in 1998, 102,400,000 tons still were shipped by the US and 82,200,000 tons iron ore were used, approximately 600 kg iron ore globally in the form of pellets are necessary to produce 1 ton steel (Energetics Inc. for US Department of Energy 2000). Therefore, one ton of steel results in 480 kg mining waste. The solid waste resulting from iron mining is **480 kg/ton salable steel.**

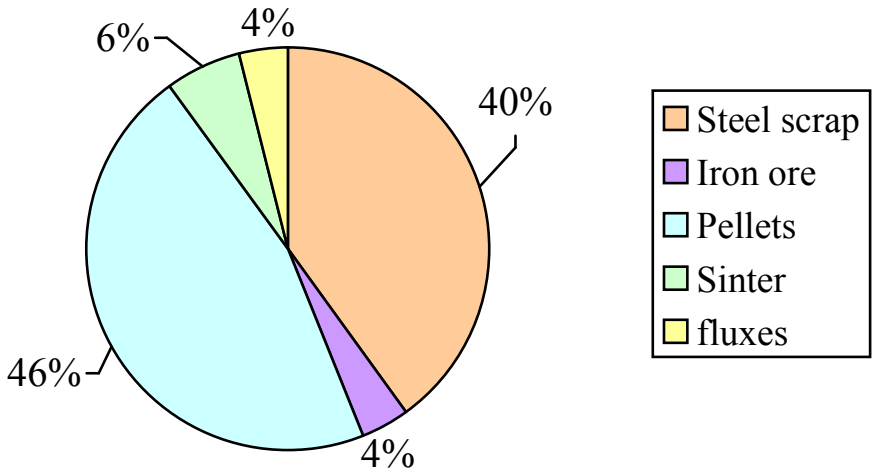


Figure 8-1 US average primary materials for steel production (Energetics Inc. for US Department of Energy 2000)

8.1.2 RCS Phase 1, air emissions resulting from material supply

Fuel combustion emissions are the only pollutant emissions that result from transportation. No subsidiary air emission or waste is noticeable.

8.1.3 RMS Phase 1, air emissions from material supply

Fuel combustion emissions are the only pollutant emissions that result from transportation. No subsidiary air emission or waste is noticeable.

8.2 Phase 2: Material purification

8.2.1 DS Phase 2, air emissions from material refining

8.2.1.1 Aluminum transfer case

Aluminum disposal scenarios are composed of two phases that are Alumina production and Electrolysis.

Alumina production

The Alumina process is mainly responsible of Mercury emissions due to Mercury content of Bauxite.

Air emissions

Beside Particulates (1 lb/ton), no important air emissions are noticeable in the alumina production (Energetics Inc. for US Department of Energy 1997).

Solid waste

As mentioned before, 2 kg of bauxite ore are necessary to produce 1 kg alumina. Therefore, the solid waste of alumina production is estimated at 500kg/ ton alumina. Given the fact that 2 kg alumina are necessary to produce 1 kg of aluminum, this is equivalent to **1 ton solid waste/ton saleable aluminum**. This solid waste is also called red mud (Energetics Inc. for US Department of Energy 1997) (International aluminum institute 2007).

Liquid waste

The water used during this process is very important. In fact, approximately 5000 kg of water are used for each ton of alumina produced. This is equivalent to **10 tons/ tons salable aluminum water consumption.**

Heavy metals

Bauxite originally constrains mercury. This heavy metal is released during the Alumina production. According to literature, mercury content in Bauxite is lower than 0.03 g/ton Bauxite that is 0.015 g/ton Aluminum (Environment Australia 1999). A 2002 Aluminum life cycle analysis (Saur 2000) estimates the Mercury air emissions at 0.1 g/ton Alumina and mercury water emissions at 0.00094 g/ton Alumina. These are averages estimated to be between 60% and 70% representative of the global Alumina industry. The global mean mercury emissions are therefore evaluated around 0.10094 g/ton Alumina that is 0.05047 g/ton Aluminum**.** The mercury emissions of Alumina processing due to Bauxite mercury's content is estimated lower than **0.05 g/ton salable aluminum.**

Electrolysis

Air emissions

The electrolysis is responsible of high and diverse air emissions. Two high global warming greenhouse gas (Perfluorocarbons) CF_4 and C_2F_6, are emitted due to the "anode effect". This effect consists in a sudden increase of voltage and decrease of amperage. It is not predictable and depends on installations. Therefore, rigorous calculation of the related air emissions is compromised. These emissions have a high global warming potential.

CF_4 (Tetrafluoromethane) resulting from Electrolysis

The CF_4 Global Warming Potential (GWP) is 6500. This means that 1 kg CF_4 has the same impact on the environment as 6500 kg CO_2. A 2000 survey performed on 200 smelters (Saur 2000) determined a CF_4 emission of 0.22 kg/ton aluminum. Another survey performed from 1990 to 2003 on five different anode prebaking technologies (MGM International 2004), gives a CF_4 mean emission of 1.3 kg/ton Aluminum in 1990 and 0.065 kg/ton Aluminum in 2003. This report also gives a detailed graph of CF_4 emissions through the years from five different technologies:

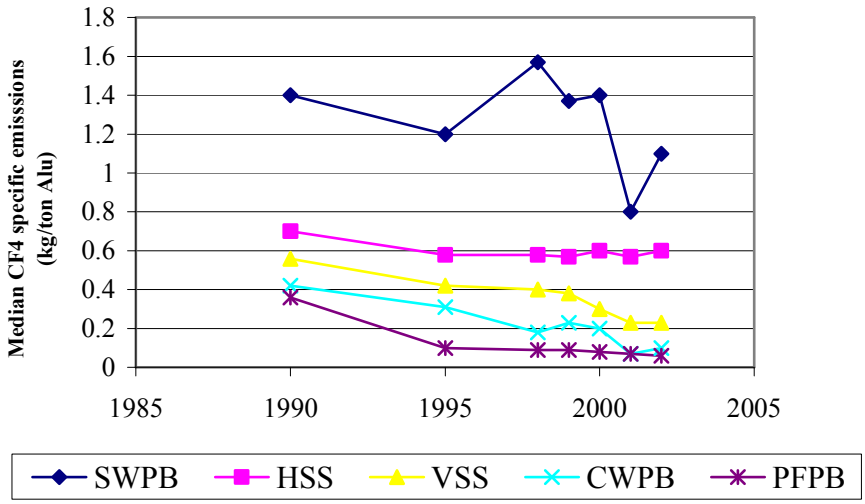


Figure 8-2 Median specific CF_4 emissions by reduction technology type from 1990 to 2002 (MGM International 2004)

The amount of CF_4 emitted by three over four technologies in 2000 is around 0.2 kg/ton Aluminum, which is coherent to first source. Therefore, CF_4 emissions will be estimated

at 0.20 kg/ton aluminum. The consequential $CO_{2\ eq}$ is estimated at **1300 kg/ton aluminum.**

C_2F_4 (Hexafluoroethane) resulting from Electrolysis

The C_2F_4 GWP is 9200. The 2000 survey performed on 200 smelters used previously (Saur 2000), gives a C_2F_4 emission of 0.021 kg/ton Aluminum emitted during Electrolysis. This emission is 10 times less than CF_4 emissions. Another survey driven from 1990 to 2003 on four different anode prebaking technologies (MGM International 2004), gives a C_2F_6 mean emission of 0.13 kg/ton Aluminum in 1990 and 0.0065 kg/ton Aluminum in 2003. This emission is also 10 times less than the CF_4 emissions given by the same source. Given the assumption of 0.2 kg/ton aluminum CF_4 and the 1/10 ratio observed in two different sources, a coherent 0.02kg/ton aluminum C_2F_4 emission will be taken as reference which is equivalent to **184 kg $CO_{2\ eq}$/ ton salable aluminum.**

8.2.1.2 Steel gear

Blast furnace: Iron making

Air emissions

Blast furnaces emit VOCs and also particulates. VOCs emissions are around 0.01 lb/ton and particulates are around 90lbs/ton. These emissions have been rarely detailed for the other processes. Therefore, these values are given here as information. No noticeable emissions come out of the molten metal.

Solid waste

Blast furnaces result in large amounts of waste in the form of Slag, Dust and sludge. There will be no difference between these three rejections. Their quantities are estimated to be approximately 13.5% of the production. Blast furnace waste rate is **135**

kg/ton salable steel (Energetics Inc. for US Department of Energy 2000). Another source gives and estimation between 200 and 300 kg/ton salable steel which corresponds to an interval of 120 kg/ton steel to 180 kg/ton steel (International finance Corporation 2007). Considering the fact that less than 1 ton Iron is necessary to create steel, these values are coherent. The waste of **135 kg/ ton salable aluminum** will be used in this study.

Liquid waste

Blast furnaces consume 6000 gallons/tons Iron of water which is 22713 kg/ton Iron (Energetics Inc. for US Department of Energy 2000). Waster waste has been estimated from 1 to 50 m^3/ ton Iron 1000 kg to 50000 kg/ ton Iron which is 600 kg/ton steel to 30000 kg/ton steel (Assuming that 600 kg Iron are necessary to create 1 ton steel) (International finance Corporation 2007). These two values are coherent and show the high water consumption of blast furnaces processes. Given the uncertainty of the ratio iron over steel created, and given the fact that less than 1 ton of iron is necessary to produce 1 ton of steel, the mean average of **15000 kg/ton steel** will be used here.

8.2.2 Recycling scenario (RCS) Phase 2

During reusable sorting, material is not transformed. No emissions come from the material. In addition to that, no other input than energy enters in the process. Therefore, no subsidiary emissions are emitted from Recycling Sorting process.

8.2.3 Remanufacturing scenario (RCS) Phase 2

Cleaning phase

In remanufacturing scenarios, the most critical phase that is susceptible to make remanufacturing harmful for the environment is the phase 2's cleaning processes because of the use of solvents. These cleaning produces have been used for decades to clean industrial systems The use of solvent in the cleaning industry in the last decade is evaluated by EPA to be 1200 Millions lbs per year (Sherman 1998).

Chlorinated products resulting from cleaning processes

The use of pollutants such as chlorinated solvents progressively decreased in the last years because of the enforcement of regulations. This decrease was possible thanks to the emergence of chlorinated solvents substitutes with lower impact on environment and especially on Ozone depletion. In the 80's CFC-113 and Methyl Chloroform (1,1,1-trichloroethane) were the solvent the most widely used in the cleaning industry. Methyl chloroform was mainly used in the metal cleaning (60% of use) (Sheppard 2004).

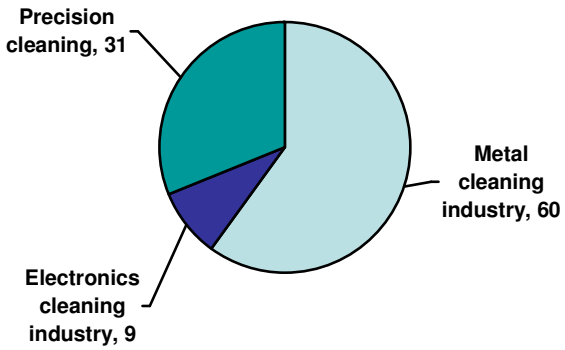


Figure 8-3 1,1,1-Trhichloroethane use, 1985

The CFC-113 was mostly used for electronics cleaning purpose, 70% was dedicated to the industrial domain and 10% of these were used in the metal cleaning industry. Some definitions are important to give before commenting the evolution of industrial solvents (US Environmental Protection Agency 2006).

Ozone Depletion potential (ODP): A number that transfers to the amount of ozone depletion caused by a substance. It is the ratio of the impact of ozone of a chemical compared to the impact of similar mass of CFC-11. Three values of ODPs are given by EPA "Ozone depleting substances" classification. These three values have been extracted by three different sources from different countries and associations. This paper will give the average of the three values.

Global warming potential (GWP): A number that refers to the amount of global warming caused by a substance. The GWP is similar to the similar mass of carbon dioxide. As for ODPs, four values of GWPs are given by the "Ozone-depleting substances" EPA classification. The values given in the current study will be the mean averages of the four EPAs GWPs.

Ozone Depleting Substances (ODS): Compound that contributes to stratospheric ozone depletions

Class I Ozone depleting Substance: One of several groups of chemicals with Ozone-Depletion potential of 0.2 or higher.

Class II Ozone Depleting Substance: A chemical with an ozone-depletion potential of less than 0.2.

Using the previous definitions, the following table 8.1 gives the impact on the environment of two industrial cleaning solvents massively used in the years 1990s. CFC-113 and Methyl Chloroform have both significant ODPs and GWP.

Table 8-1 Cleaning solvents characteristics (US Environmental Protection Agency 2006)

Chemical name	Life time in years	ODP	GWP
CFC-113 (C2F3Cl3)	85	1	5500
Methyl Chloroform (C2H3Cl3) Trichloroethane	5	0.1	131.5

Because of the high global warming and ozone depleting potentials given Table 8.1, CFC-113 and Methyl chloroform consumption were massively reduced in the 1990 with the Montreal protocol. This protocol prohibited the use of high Ozone depleting substances such as these two ozone depleting solvents (ODS).These two solvents were classified as Class I ODS and had to be replaced in 1996 by other solvent with lower ODP. Some temporary substitutes were developed in the 1990s, the HCFCs. They were classified Class II ODS. These substances had lower ODPS but still important. They were progressively replaced by other techniques and solvent judged less harmful for the ozone. These solvent are identifies as following and detailed in Table 8.2.

Hydrochlorofluorocarbon (HCFC): A compound consisting of hydrogen, chlorine, fluorine and carbon used to replace CFCs. They contain chlorine, but to a much lesser

extent than CFCs (ODS = 0.01). They are classified as Class II in the ozone depleting EPA organization.

Hydrofluorocarbon (HFC): A compound consisting of hydrogen, fluorine and carbon. The HFC are a class of replacement for CFCs. Because they do not contain chlorine, they do not deplete the atmosphere. (ODS = 0). Some HFC have high GWPs.

Aqueous cleaners: Solvents that consist of 60% or more of water with a flashpoint greater than 199 F. They are miscible to water (Environmental Protection Agency 1999; Kansas Administrative Regulation 2006).

Semi-Aqueous: "Semi Aqueous processes […] use a cleaning solution often a hydrocarbon/surfactant combination, to remove contaminants such as metal particulates, oil and grease followed by a water wash and rinse […] Semi-Aqueous solvents have not maintained as strong a presence in the US as aqueous cleaning." (US Environmental Protection Agency 2004)

Table 8-2 Cleaning solvents and solutions used in the metal cleaning industry (US Environmental Protection Agency 2004)

Organic solvents	Solvent	Formula	Marfeted name	ODP	GWP	Other characteristics
Fluorinated Solvents	Hydrofluorocarbons HFC	HFCPA	Zeorara-H®	0	250*	High boiling point
		HFC-4310mee	Vertel® Specialty solvents	0	1500**	
	Hydrofluoroethers HFE	HFE 7000	Novec®	0	400	No VOC
		HFE 7100		0	390*	
		HFE 7200		0	55*	
	hers PFC/PFE	(greated than 8900) and long atmosphere living time (3200 y)				
Chlorinated Solvent	Perchloroethylene PCE	Classified as HAP, by CAAA 1990 Title III. Because of chlorinated health and air pollutions, their demand in the indsutry dropped by 70 % from 1987 to 2001				cold use, non-flammability
	Trichloroethylene TCE					Aggressive, solvent, excellent solvency, Low-flammablity, Low boiling point, Cancer risks
	Methylene chloride MC					Excellent solvency, Cold or vapor degrasing, aggressive solvency
TRANS	Trans-1,2-Dichloroethylene	C2H2Cl2 (C2h)	Vertrel®, Techspray®, Genesolv®,	0	Short life time in atmosph	degreasing Might be dangerous for the user
Brominated Solvents	n-Propyl bromide (nPB)	C3H7Br	Solvon ® ABZOL ® Ensolv ® Lenium ®	0.013 to 0.018 (US)	0.31	Corrosion, fllammability Health hazardous
Aqueous	Water	H2O		0	0	High water consumption, mechanical agitation or hot temperature required, drying processes required
Semi-Aqueous	Hydrocarbon-surfactant					VOCs emissions, heated rinses and drying required, less water than aqueous required.

These solvents have been recognized by EPA as acceptable substitutes for ozone-depleting substances. As specified in Table 8.2, some of them have shown their limit environmental and health impact. Chlorinated solvent were manufactured to replace punctually ODS. These chlorinated solvents happened to be health hazardous for the users and were forbidden in 1990. The same way, the current accepted use of n-Propyl

Bromide to replace chlorinated solvents and ODS is controversial because of its potential health impact. This study will take in consideration the solvents accepted from EPA as valuable substitutes for high polluting solvent such as ODS and chlorinated solvents.

Table 8.3 shows how fluorinated solvents and other new technologies substituted progressively the harmful and now forbidden substances such as CFCs and other ozone depleting solvents.

Table 8-3 Cleaning substitutes (US Environmental Protection Agency 2000)

Organic solvents	Solvents	Substitute for:					
		ODS Type I		ODS Type II	Chlorinated solvents		
		CFC	Methyl chloroform	HCFC	PCE	TCE	MC
Fluorinated Solvents	Hydrofluorocarbons HFC	CFC-113					
	Hydrofluoroethers HFE	CFC-113	Methyl chloroform	HFC-141 b	Chlorinated solvents		
TRANS (Combined with fluorinated solvents)	Trans-1,2-Dichloroethylene	CFC-113	Methyl chloroform	HFC-141 b			
Brominated Solvents	n-Propyl bromide (nPB)	CFC-113	Methyl chloroform	HFCFs	Perchloroethylene and Tetrachloroethylene		
Aqueous	Water	ODS					

Figure 8.3 shows the use of solvents in the metal industry. In reality, a few percent of metal cleaning is also realized with semi-aqueous solutions and other cleaning technologies (No-clean) (Sheppard 2004).

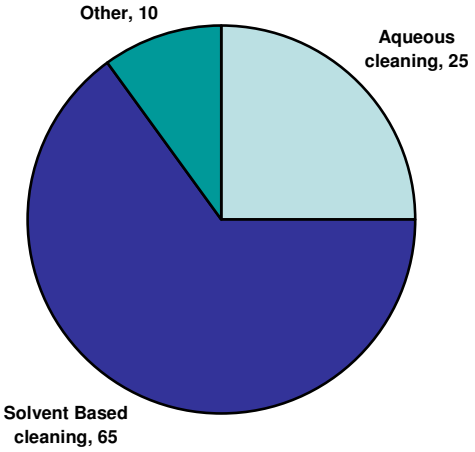


Figure 8-4 Metal industry cleaning use by product

Table 8-4 Solvents used for metal cleaning (US Environmental Protection Agency 2004)

Category	Chemical definition	Formula	ODP	GWP	Cost	pH & boiling point
Fluorinated Solvents	Hydrofluorocarbons HFC	HFCPA	0	250*	$23/lb	BP= 80 C
		HFC-4310mee	0	1500**	$18/lb	pH= Neutral BP= 55C
	Hydrofluoroethers ** HFE	HFE 7000		400	$16/lb to $17/lb	BP=34 C
		HFE 7100	0	390*		BP= 61C
		HFE 7200	0	55*		BP= 76C
Brominated Solvents	n-Propyl bromide (nPB)	Controversial substitute to chlorinated solvents due to high ODP and health hazards.	0.013 to 0.018 (US)	0.31	$4/lb	pH= 6.5 to 7.5 BP= 87 C
Aqueous	Water	H2O	0	0 from product	$4.10024/lb*	pH= Neutral BP = 100 C

* Price of US electricity = 10c/kWh
Price of US water = $0.002/gal = $0.00024/lb
** pH does not apply for Hydrofluoroethers

The cleaning solutions given in Table 20 are usually used in the industry for aluminum and steel application (Chesterton 2007). Fluorinated solvents have no ozone depletion impact but have significant global warming potential, whereas nPB has very low impact on the environment but important impact on the users' health as demonstrated Table 22. Therefore, aqueous cleaning appears to be the best issue from a pollution point of view. This conclusion is disputable given the fact that aqueous cleaning request hot

temperatures, mechanical movements and drying processes to prevent metal corrosion. These supplementary processes increase cost, energy consumption and therefore increase air emissions. Another important fact that is demonstrated Figure 8.2 is that water is less efficient than other solvents in term of quantity. Therefore, for the same result as nPB or HFEs, higher quantities of water are necessary resulting in higher waste. This is why concluding to a systematic use of water because of its positive environmental impact compared to other solvents would be biased. Next section will evaluate the actual environmental and health impact of each solvent by taking in consideration all influent parameters.

The air emissions of each solvent described previously are going to be evaluated. The emissions are assumed to be the same in vapor treatment as in room temperature treatment. All solvents are assumed to be rejected in the atmosphere after use due to immediate evaporation (Drying, low boiling point, or during later rinsing water disposal treatment). The atmospheric rejections rates have been evaluated thanks to maximum emissions voted by EPA for users' health protection or thanks to usual industrial cleaning procedures. Table 8.5 gives cleaning solvents use rates or maximum emissions levels.

Table 8-5 Use of solvent by quantity

Solvent	Maximum level authorized	10 ^6 L Room (35 315 cubic feet)
HFCPA	123 ppm (8hr*)	123 L
HFC-4310mee	200 ppm (8hr*)	200L
HFE 7000	No data	No data
HFE 7100	750 ppm	750 L
HFE 7200	200 ppm (8hr*)	200 L
N-Propyl Bromure	25 ppm	25 L

The use of N-Propyl Bromure is the most restricted compared to other solvents. This is due to its controversial and potential hazard on health. Given Table 8.5, in two independent rooms of a same volume $(10^6 L)$, 30 times more HFE 7100 can be used than N-Propyl Bromure. Consideration the safety laws, HFE 7100 appears to be the most indicated and NPB the most dangerous. The safety coefficients of all solvents given Table 8.5 are given Table 8.6 relatively to NPB.

Table 8-6 Relative safety between solvents and nPB

Solvent	Relative use proportion between solvents
HFCPA	4.92
HFC-4310mee	8
HFE 7000	No data
HFE 7100	30
HFE 7200	8
N-Propyl Bromure	1

In order to complete this comparative analysis, in addition to the health hazard parameter, the solvent efficiency will also be taken in consideration. In the following, the efficiency of these two solvents will be taken in consideration to determine the quantity necessary to clean a given surface.

N-Propyl Bromure is the most restricted solvent with 25 ppm emissions allowed in a working room and HFE 7100 is the most harmless solvent for workers with 750 ppm allowed. It is also the most commonly HFE solvent used in the cleaning industry (3 M Novec 2001). N-Propyl Bromure manufacturers advise a consumption of 0.04 lb/hr ft^2 in case of light dirt or simple surfaces (no holes, no asperity, smooth curves) to 0.6 lb/hr ft^2 in case of heavy dirt and complex geometry, whereas HFE 7100 manufacturers warranty

the efficiency of their product with a consumption of 0.03 lb/hr ft^2 to 0.1 lb/hr ft^2 (Kehren 2007). The HFE 7100 is 30 times less harmful for health given EPA scale and more efficient than n-Propyl Bromide. Nevertheless, HFE 7100 has a GWP of 390 as nPB has a GWP of 0.31. HFE 7100 is also 4 times more expensive than nPB (Table 8.4).

In order to evaluate the emissions due to cleaning processes, the aluminum transfer case housing and the steel gear will be used. Table 8.7 gives the approximate time to clean those two parts and the corresponding consumption of solvent. Water use will also be calculated in Table 8.7.

Table 8-7 Cleaning solvents consumption (Kehren Jason 2003)

	Solvent	Industrial consumption rates	Max cleaning time advised	Solvent consumption /part
Aluminum transfer case Contenance volume = 8 L Part volume = 1.5 L Housing surface = 1.7 ft2	HFE 7100	0.03 to 0.1 lb/hr ft2	10 min	0.008 to 0.028 lbs
	N-Propyl Bromure	0.04 to 0.6 lb/hr ft2	10 min	0.011 to 0.17 lbs
	H2O	100L	5 to 30 min	17L Assuming: 1/3 of tank volume = parts 2/3 of tank volume = water
		400L	5 to 30 min	
Steel gear Contenance volume = 1L Part volume = 0.8 L Part surface = 0.86 ft2	HFE 7100	0.03 to 0.1 lb/hr ft2	10 min	0.004 to 0.014
	N-Propyl Bromure	0.04 to 0.6 lb/hr ft2	10 min	0.006 to 0.086
	H2O	100L	5 to 30 min	2 L Assuming: 1/3 of tank volume = parts 2/3 of tank volume = water
		400L	5 to 30 min	

The resulting environmental impact of the solvents determined Table 8.7 is given Table 8.8 in term of g $CO_{2\ equivalent}$. The estimation was possible thanks to the GWPs given Table 8.4. As mentioned in the glossary, GWP "is GWP is similar to the similar mass of carbon dioxide." In the case of HFE 7100, given the GWP of 390, 1 g of HFE 7100 rejected in the atmosphere has the same environmental impact as 390 g of CO_2. This

calculation has been performed for HFE 7100, nPB and water. The results are exposed Table 8.8.

Table 8-8 Environmental impact of cleaning solvents in term of CO_2 eq

Parts characteristics	Solvent	g CO2 equivalent/ton metal
Aluminum transfer case Envelop volume = 8 L Part volume = 1.5 L Housing surface = 1.7 ft2	HFE 7100	1415 to 4950
	N-Propyl Bromure	1.3 to 24
	Water	0
Steel gear Contenance volume = 1L Part volume = 0.740 L Part surface = 0.86 ft2	HFE 7100	708 to 2477
	N-Propyl Bromure	0.8 to 12.2
	Water	0

8.3 Phase3: Material's properties modification

8.3.1 Disposal scenarios Phase 3

Given the assumption that aluminum is directly cast after electrolysis, the Phase 3.1 is not applicable to disposal strategies. This fact is also valid for steel applications.

8.3.2 Recycling scenarios (RS) Phase 3, processes air emissions

8.3.2.1 Aluminum transfer case

Aluminum melting

Air emissions

Primary and secondary aluminum is generally polluted by alkali impurities and non-metallic inclusions (Sahai 2006). Aluminum refining is realized by adding solvents or gas. This process is called *fluxing* (Environmental Protection Agency 2005). There are

two types of fluxing. The most used and generally necessary is realized with Dross-only furnaces. These furnaces reclaim the aluminum that results from drosses during melting and holding operations taking place in other furnaces. The exposition of molten aluminum to the atmosphere results in oxidation of the surface. Flux such as salt flux is added and reacts with impurities such as Alkali metals, inclusions (Na, Li, Ca….) and hydrogen present in the molten metal and creates "dross" (Bridi 2006). The second technique is called "In-Line flux". This process is typically used in high quality manufacturing or in plants that are specialized in metal degassing. This is not exactly applicable in this study. Nevertheless, the emissions will be given with an informative purpose to the lecturer. The in-line processes consist in injecting inert gases such as Chlorine, Argon, Nitrogen and other gases "to achieve the desired metal purity". Argon and Nitrogen do not emit any HAPs. On the contrary, Chlorine use is responsible of HCL emissions (Environmental Protection Agency 1999).

Two types of emissions are determined by EPA's regulations. The respective emissions of Dross-Furnaces and in-Line Flux are determined Table 8.9. The emissions presented here are "uncontrolled" emissions. They are total emissions of the process without considering any filter or post sequestration.

Table 8-9 Secondary (and Primary) Aluminum melting emissions (Environmental Protection Agency 1999)

Refining Process	Uncontrolled Emissions	
	PM	HCL
Salt Flux	6200 g/ton Alu	
In Line Flux		1300 g/ton Alu

Water waste

The water use of aluminum melting is evaluated at **320 kg/ton Aluminum molten** (Energetics Inc. for US Department of Energy 1997).

Solid waste

The solid waste also called metal dross, is composed of impurities and also metal. It is a residue resulting from aluminum melting processes. It is difficult to evaluate a general composition Therefore, a content of 50% pure metal will be assumed in the metal dross resulting from aluminum melting processes. The amount of dross also depends on the technology used to melt the metal. However, assuming a general ratio of 5% is realistic (Metals advisor 2005).. Therefore, the ratio of aluminum loss during melting over aluminum molten is 0.025, which drives to a loss of **25 kg/ton salable aluminum**.

8.3.2.2 Steel gears

Steel Melting

Waste water

Basic oxygen furnaces (BOF) have very important water consumption. In fact, an average of 4206 kg/ton steel molten of water is needed. The waste water evaluated by other sources is from 0.5 to 5 m^3/ton salable steel which corresponds to 500 kg/ton to 5000 kg/ton salable steel for basic oxygen furnaces and 3 m^3 /ton steel which corresponds

to 3000 kg/ton steel for electrical arc furnaces (EAF). In this study, the mean average between the maximum water consumption of basic oxygen furnaces and the water waste generated by electrical arc furnaces is **4000 kg/ton steel**. This result will be used for the melting process. Even if in reality, electrical arc furnaces appear to generate less water waste than BOF, there will be no distinction between the two processes water waste.

Solid waste

As developed in Chapter 5, two types of furnace are used to melt steel. The Basic Oxygen Furnace uses Pig Iron coming out of the Blast furnace and small quantities of scrap steel, whereas EAF use 100% of scrap steel. Given the different types of primary material these two furnaces use, their solid waste differs as well. In fact BOF solid waste (slag, dust and sludge) is evaluated at **85 kg/ton salable steel,** whereas EAF furnaces waste is evaluated around **50 kg/ton salable steel** (Energetics Inc. for US Department of Energy 2000). Other sources lead to a solid waste generation of **85 to 110 kg/ton salable steel** for BOF and **110 to 180 kg/ton steel** for EAF (International finance Corporation 2007). These data are contradictory. In fact, regarding the first values, BOF generate more solid waste than EAF, whereas regarding the second values, EAF emit more waste than BOF. This is due to the fact that the first wastes have been calculated with national waste values over one year (1997) and compared to the US national annually global steel production. Therefore, the results do not take in consideration individual steel production of each furnace. Nevertheless, even if these results are different, they are all around a waste amount of **110 kg/ton salable steel.**

8.4 Phase 4: Definition of material's final functionality

8.4.1 Disposal scenarios (DS) Phase 4, processes air emissions

8.4.1.1 Aluminum transfer case

Aluminum casting

During casting, the molten metal is poured or injected into a mold. The mold is then held under pressure during a given time. The pressure is then released and the part is ejected from the mold. In order to avoid any sticking between the mold and the part that would damage or destruct the part, "Refractory wash" also called "parting agent" or "mold release agent" is prayed regularly on the contact walls of the mold. These agents are composed of various substances such as alkaline salts, hydrocarbon solvents (Butane, Propane), wax, Silicone Dioxide, etc…(Otto Bock 2006) (Silicone agent A FAIRE; VACUDEST- Pratique 2005). In contact with hot metal, part of the agents vaporize in the atmosphere and create air pollution and hazardous vapor for workers. These emissions are mostly composed of CO_2, CO, resulting from the combustion of hydrocarbons, silicone dioxide and other pollutants depending on the composition of the mold wash. The emissions are difficult to estimate given the fact that agent do not vaporize completely and remain in the mold until the end of the part casting. This is why, after each casting procedure, the walls of the mold are rinsed with large amount of water. This disposed water is not highly polluted. In fact, casting disposed water are generally composed of 95 to 99% of water (VACUDEST- Pratique 2005). Therefore, in this phase, given the incomplete vaporization of the mold release agent, given the small quantity of agent used on the mold's walls and finally, given the large amount of water disposed

compare to the amount of polluting agent disposed, only the water waste will be considered in the casting process.

8.4.1.2 Steel gear

Gear casting

NOx

Continuous casting is responsible of 0.05 lb/ton steel NOx emissions. That corresponds to **0.025 kg/ton steel.**

Water waste

Continuous casting makes use of water as cooling systems and flume purification. The amount of water is estimated at 25 gallons/ton which is equivalent to **105 L/metric tons steel** (Energetics Inc. for US Department of Energy 2000). The water consumed during casting is estimated by other sources to be between 1000kg/ ton to 15000 kg/ton steel (International finance Corporation 2007). The data are not coherent in this case. Therefore, the minimum consumption of **105 L/metric tons steel** will be used here. This choice is done here because at least this quantity of water is used in both data found in the literature.

Solid waste

Steel casting processes result in a solid waste evaluated at **75kg/ton salable steel** (Energetics Inc. for US Department of Energy 2000). Another source gives a solid waste estimation of **70 to 150 kg/ton salable steel**, which is coherent with the value given before. Therefore, a casting solid waste generation will be estimated at **75 kg/ton salable steel.**

Heavy metals

Traces of chromium, copper and Selenium can be found in continuous casting *waste water*

8.4.2 Disposal scenarios (DS) and Recycling (RCS) Phase 4, processes air emissions

Liquid waste and air emissions

An important component of the machining process is the lubrication. The lubrication consists in a continuous or discrete but repeated pulverization of fluid on the machining point and has important roles of cooling, lubrication, anti-bacteria and also corrosion and rust inhibitor. These four main functions are summarized and detailed Table 8.10.

Table 8-10 Cutting fluid properties

Cutting fluids functions	Effect
Lubricant	Preserve material and tool from fusion
Coolant	Preserve material from ponctual dilatation and consequential microstructure damage
Anti-bactery	Prevent fluid from bacterial growth and rancid
Anti-corrosion and rust	Protect the tool and part from corrosion and rust

There exist different types of cutting fluids. Straight cutting oils, soluble oils, synthetic, semi-synthetic oils, gases and solid lubricants are the most developed and used in the industry (Booser 1993) (Machine Shop 1 2007). The main components of soluble oils are bactericide, water and mineral oils mixed homogeneously with the addition of emulsifiers. These emulsifiers break the oil into small globule and make it miscible in water. With correct proportions, the resulting lubricant combines the cooling properties

of water and the anti-corrosive and lubricant properties of oil. Oil and water characteristics are summarized in Table 8.11. This table shows how the combination of the two elements drives to one lubricant with great properties of lubrication, flammability, rust inhibitor and cooling.

Table 8-11 Water and oil properties

Property	Low flammability	Lubrication capacity	Rust inhibitor	Coolant properties
Water	+++	---	---	+++
Oil	---	+++	+++	---
Association Water + Oil	+++	+++	+++	+++

"*Straight cutting oils or Neat oils are Petroleum based mineral oils, reinforced with "Extreme Pressure additives*" such as Sulphur or Chlorine additives (Saint-Gobain abrasives 2007). Synthetic and semi-synthetic will not be considered in this study regarding their poor lubricity and other use limitation such as high pollution (high detergency capacity) and poor surface finish results. The lubricants contain additives that improve their quality. These additives are described Table 8.12.

Table 8-12 Additive properties (Machine Shop 1 2007) (US Department of Labor 2007)

Addittive	Action	Example
Emulsifier	Breaks oil into small globules, makes oil and water miscible	Petroleum sulfonate, salts of fatty acids, non ionic srfractants
Rust and corrosion inhibitor	Prevents the rust and corrosion resulting from water and additives	Clacium sulfonate, sodium sulfonate, fatty acid soaps, amines
Bactericide	Controls the gorwth of bacteria in lubricant	Triazine, oxadolidine
Sulphur additive	Increases cooling and lubricating qualities of oils, helps prevent welding of chip tool	
Chlorine additive		
Fatty/lard oil	Act as wetting agent and improve lubrication of oils	Animal fat

The association of oils, water and the additives determined Table 8.12, drive to high quality lubricants. The most industrially used fluids are summarized Table 8.13.

Table 8-13 Industrial lubricant compositions (Saint-Gobain abrasives 2007)

Lubricant	Composition
Soluble oils/ emulsions	Water + Oil + emulsifier +bactericide
Straight/ neat cutting oils	Mineral oils + sulphur
	Mineral oils + fatty oils (up to 40%)
	Mineral oils + Chlorine
	Mineral oils + Sulphur + Fatty oils
	Mineral oils + Sulphur + chlorine

Table 8.14 shows the typical compositions of these metal working lubricants determined through a European survey (Organization for Economic Co-operation and Development 2004).

Table 8-14 Metal cutting oils composition (Organization for Economic Co-operation and Development 2004) (Saint-Gobain abrasives 2007)

	Mineral oils	Fatty oils	Sulphurized fat	Sulphur	Chlorinated Paraffin	Emulsifier	Corrosion inhibitor	Water	Biocides
Soluble oils/ Emulsions	75%	0	0	0	0	15%	6%	2%	2%
Neat oils composition									
Straight oils	100%	0	0	0	0	0	0	0	0
Fatty mineral oils	90%	10%	0	0	0	0	0	0	0
Chlorinated fatty mineral oils	85%	5%	0	0	10%	0	0	0	0
Sulphurized mineral oil	90%	0	10%	0	0	0	0	0	0

Given to lack of information concerning the content of sulfur in sulphurized fats, 30% will be assumed. Therefore, given the fact that sulphurized mineral oils contain 10% sulphurized fat, the resulting total sulfur content is 3% (H&B Industries INC. 2007). Chlorinated paraffin's chlorine content varies between 40% and 70% depending on the type of application and other parameters such as operation difficulty (Organization for Economic Co-operation and Development 2004) (Whelan 1994). A generalized concentration of 55% will be considered in this study. This assumption resulting in chlorinated neat oil total chlorine content of 5.5%. Most of the chlorinated solutions found on the market are also sulphurized based. This drives to a concentration of chlorine much smaller than the 5.5% assumed. Most of the time, the sold products observed have a chlorine concentration varying from 0.25% to 2% (Milacron Marketing Co. 1999) (H&B Industries INC. 2007).

Neat oils are used pure, whereas soluble oils are diluted with water. The dilution rate of soluble oils depends on the machining process used. In this study, the global dilution ratio oil: water will be generally considered as 1:20 for milling and turning processes and 1:10 for drilling processes. This ratio is used and validated by different sources (Organization for Economic Co-operation and Development 2004) (H&B Industries INC. 2007; Machine Shop 1 2007). Table 8.15 is given as information.

Table 8-15 Soluble oils ratios by process (Organization for Economic Co-operation and Development 2004)

Processes	Concentrate:Water
Broaching	1:10 to 1:5
Thread cutting	1:20 to 1:10
Drilling	1:10
Milling	1:20
Turning	1:20
Sawing	1:20 to 1:5
Grinding	1:20 to 1:50

The type of lubricants used for a specific process is given Table 8.16.

Table 8.16 Cutting fluids by machining processes (Machine Shop 1 2007)

Material	Milling	Drilling	Tapping	Turning
Aluminum	Soluble oil (oil:wat = 1:20)	Soluble oil (oil:water=1:10)	25% Sulfure based oil + mineral oil	Mineral oil + 10% soluble oil (oil:wat = 1:20)
Steel	10% lard oil + 90% mineral oil	Soluble oil (oil:water=1:10)	30% lard oil + 70% mineral oil	25% Sulfur base oil + 75% mineral oil

Table 8.17 Lubricant composition by process and by material processed

	Material	Hydrocarbure	Water	Sulphur	chlorine	Emulsifier	Anti corrosion	biocides
Milling	Aluminum	3.50%	95%	0%	0%	0.75%	0.30%	0.10%
	Steel	100%	0%	0%	0%	0	0	0
Drilling	Aluminum	7.70%	90%	0%	0%	1.50%	0.60%	0.20%
	Steel	7.70%	90%	0%	0%	1.50%	0.60%	0.20%
Turning	Aluminum	94.0%	9.50%	0%	0%	0.08%	0.03%	0.01%
	Steel	99.25%	0%	0.75%	0%	0%	0%	0%
Tapping	Aluminum	99.25%	0%	0.75%	0%	0%	0%	0%
	Steel	100%	0%	0%	0%	0%	0%	0%

In order to calculate the emissions and waste resulting from lubrication, the consumption rate of lubricant has to be determined. In the last years, studies helped to determine a Minimum Quantity of Lubricant (MQL) for metal cutting processes. This minimum rate can be as small as 100mL/h or less (Li 2006) (Inoue 2005). This technique is not widely used in the industry and requires highly refined oils and specific installations. MQL technique is considered out of the boundary of the study. The other lubrication techniques use cutting fluids in much higher proportions. Flow rates given in the literature are diverse depending on the process and the companies, but the global magnitude is around 600 L/hour (Benes 2007) (Nogacool 2007) (SHERA BONNET & Associates Pty Ltd 2007). According to the 1:20 ratio of concentrate soluble oil: Water for milling and turning processes and the ration 1:10 for drilling processes, the consumption rate of lubricants and additives by process is given Table 8.15. The general consumption rate of lubricant is assumed to be 600 L/h, the lubricant consumption rates are calculated with the compositions rates determined previously in Table 8.14 and 8.16.

In order to identify the quantity of lubricant and additives used for the production of the aluminum transfer case and the steel gear, the time of metal machining is necessary. In order to perform these calculations, chapter 5 machining calculation will be used. For a better understanding, the formula and the manufacturing phases used are briefly reminded Equation 8.1 and Equation 8.2.

V_f [mm/min] = Advance speed = $f_z \times n \times Z_n$ [8.1]

With: f_z = Teeth advance [mm]

n = Rotation speed [tr/min]

Z_n= Number of tooth

Q [cm^3 /min] = Chip volume = $a_p \times a_e \times V_f$ [8.2]

With a_p = Tool axial pass depth [mm]

a_e = Radial pass depth [mm]

V_f = Advance speed [mm/min]

Figure 8.5 and Figure 8.6 illustrate the geometrical specifications used in the previous equations. Figure 8.5 shows the case of a drilling process. The advance direction is toward the machined part (in this representation it is vertical and going down). The diameter of the hole is the same as the diameter D of the tool.

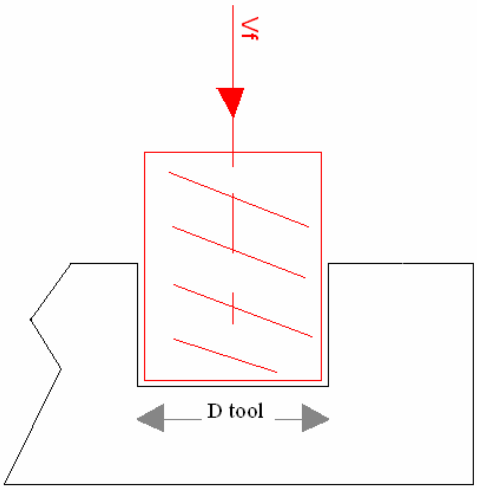


Figure 8-5 Drilling process

Figure 8.6 illustrates an end-milling process. This process will be preferred for surface machining instead of profile machining. The radial path depth is defined as *ae* and the axial pass depth is defined as *ap*.

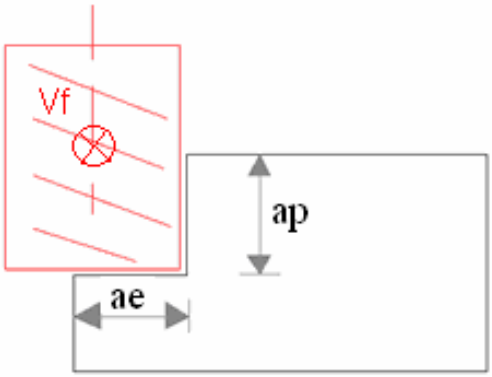


Figure 8-5 End milling example

The machining phases for an aluminum transfer case housing are reminded Figure 8.7. The removed material is determined by a red/dark color. The process that removes the material is specified on the Figure. The number following the process name is the order of process. For instance, end milling 1, is the first milling process that is performed.

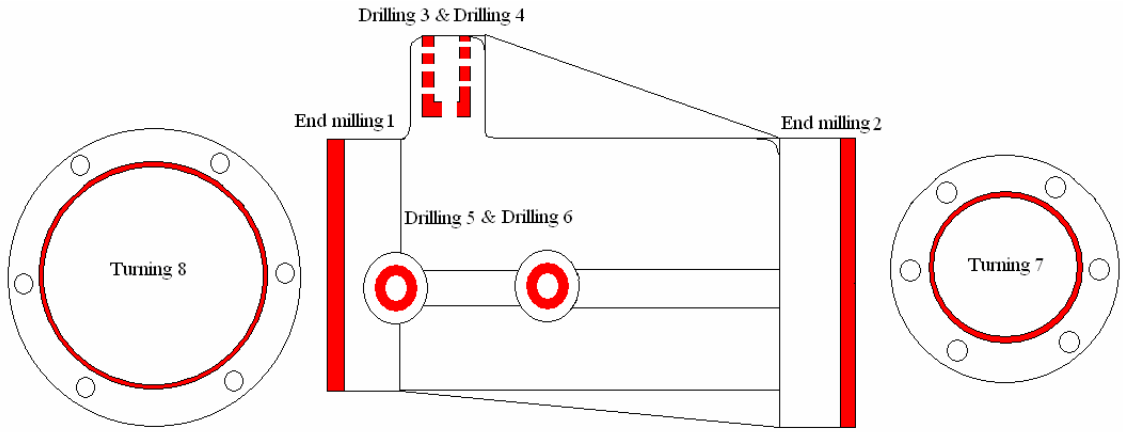


Figure 8-7 cutting phases chronology

The phases determined on the previous Figure are organized in Table 8.16. The associated dimensions are given and lead to the calculation of the volume removed and the operation time. This operation time is important to determine how much lubricant will be consumed.

Table 8-16 cutting operations dynamic specifications

			Value [mm]	Volume removed [mm3]	Removal rate [mm3/sec]	Single Operation time [sec]	All operations time [sec]
1	1 X Milling	Extern diameter	200	54400.5	5000	10.9	10.9
		Intern diameter	130				
		Depth	3				
2	1 X Milling	Extern diameter	225				
		Intern diameter	150				
		Depth	3	66234		13.2	13.2
3	6 X Drilling	Extern diameter	6				
		Depth	18	508.7	523	0.97	5.82
4	6 X Drilling	Extern diameter	8				
		Depth	15	754	930	0.8	4.8
5	2 X Drilling	Extern diameter	9				
		Depth	25	1590	523	3	6
6	2 X Drilling	Extern diameter	9				
		Depth	30	1907.5	523	3.7	7.4
7	Turning	Extern diameter	135				
		Intern diameter	130				
		Depth	15	6076	892	6.8	6.8
8	Turning	Extern diameter	155				
		Intern diameter	150				
		Depth	5	5985.7	1026	5.8	5.8

Table 8.16 operation times are used in Table 8.17 to determine how much lubricant is consumed for each phase of the aluminum transfer case machining. As mentioned before, the lubricant consumption rate is assumed to be 600 L/h.

Table 8-17 Aluminum transfer case lubricant consumption

	Aluminum part (Lub flow rate = 600L/h]		
	Machining phases	Machining time (sec)	Lubricant quantity (L)
1	Milling	10.9	1.8
2	Milling	13.2	2.2
3	Drilling	5.8	1
4	Drilling	4.8	0.8
5	Drilling	6	1
6	Drilling	7.4	1.2
7	Turning	6.8	1.1
8	Turning	5.8	0.97

Eventually, as it was shown Figure 8.16 and 8.17, lubricant have different compositions depending on the process and the material. Table 8.18 details the composition of the lubricants used during each machining phase.

Table 8-18 Lubricant and additives consumption from aluminum transfer case machining

Machining phases	Lubricant quantity (L)	Hydrocarbure (L)	Water (L)	Sulphur (L)	Chlorine (L)	Emulsifier (L)	Anti corrosion (L)	Biocides (L)
1 X Milling 1	1.8	0.06	1.72	0	0	0.014	0.00545	0.0018
1X Milling 2	2.2	0.077	2.09	0	0	0.0165	0.0066	0.0022
6 X Drilling 3	1	0.074	0.87	0	0	0.0145	0.0058	0.0019
6 X Drilling 4	0.8	0.006	0.72	0	0	0.012	0.0048	0.0016
2 X Drilling 5	1	0.077	0.9	0	0	0.015	0.001	0.02
2 X Drilling 6	1.2	0.0924	1.08	0	0	0.018	0.0012	0.024
1 X Turning 7	1.1	1.034	0.0649	0	0	0.00088	0.00033	0.0011
1 X Turning 8	0.97	0.9118	0.05723	0	0	0.000776	0.000291	0.00097
Total / Aluminum part	**10**	**2.3**	**7.5**	**0**	**0**	**0.09**	**0.02**	**0.05**
Total / ton Aluminum	**2440**	**561**	**1830**	**0**	**0**	**22**	**5**	**12**

Solid waste

As it is calculated in Table 8.16, aluminum transfer case total volume removed is approximately equal to 135 cm^3. Given the fact that the part is 1.5 L, 9% of the final volume has been removed. This results in 37 g/ part aluminum waste and **90 kg/ton salable aluminum.**

8.4.2.2 Steel gears

The material removed during disposal scenarios machining processes is shown Figure 8.8. The red/dark color illustrates the material that is removed from the part.

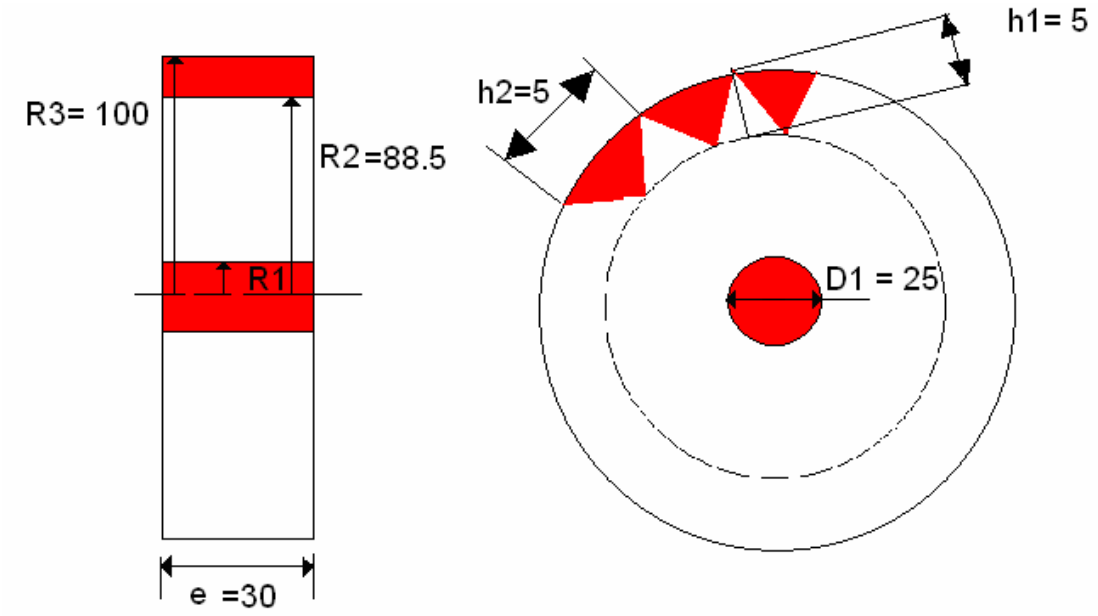


Figure 8-8 steel gear cutting phases chronology

The same way it was done in the aluminum transfer case application, Table 8.19 helps to determine the operation time.

Table 8-19 cutting operations dynamic specifications

Steel gear machining			Value [mm]	Volume removed [mm3]	Removal rate [mm3/sec]	Single Operation time [sec]	All operations time [sec]
1	1 x Drilling	Exterior Diameter	20				
		Depth	30	9420		7.85	7.85
2	1 x Turning	Exterior Diameter	25				
		Interior Diameter	20				
		Depth	30	5299		4.4	4.4
3	1 x Turning	Exterior Diameter	200				
		Interior Diameter	25		1200		
		Depth	3	92728		77.3	77.3
4	1 x Turning	Exterior Diameter	200				
		Interior Diameter	25				
		Depth	3	92728		77.3	77.3
5	N xMilling	Tool Diameter	100				
		Tooth depth	5	125 x 12.5		0.01	1.25

Using Table 8.19 results, the lubricant quantity is evaluated in Table 8.20.

Table 8-20 steel gear lubricant consumption

	Steel part (lub flow rate = 600L/h)		
	Machining phases	Machining time (sec)	Lubricant quantity (L)
1	Drilling	7.85	1.31
2	Turning	4.4	0.73
3	Turning	77.3	12.9
4	Turning	77.3	12.9
5	Milling	1.25	0.21

And eventually, the composition of the lubricants used in each phase is calculated in Table 8.21.

Table 8-21 Lubricant and additives consumption during steel gear machining

Steel gears machining lubricant consumption								
Machining phases	Lubricant quantity (L)	Hydrocarbure (L)	Water (L)	Sulphur (L)	chlorine (L)	Emulsifier (L)	Anti corrosion (L)	Biocides (L)
1 x Drilling	1.31	0.10087	1.179	0	0	0.01965	0.00786	0.00262
1 x Turning	0.73	0.724525	0	0.005475	0	0	0	0
1 x Turning	12.9	12.80325	0	0.09675	0	0	0	0
1 x Turning	12.9	12.80325	0	0.09675	0	0	0	0
125 xMilling	0.21	0.21	0	0	0	0	0	0
Total / Steel gear	**28.05**	**26.6**	**1.17**	**0.2**	**0**	**0.02**	**0.007**	**0.002**
Total/ ton steel	**4488**	**4263**	**188.6**	**31.8**	**0**	**3.15**	**1.258**	**0.42**

Solid waste

As it is calculated in Table 8.19, steel gear total volume removed is approximately equal to 202 cm^3. Given the fact that the part is 0,75 L, 26% of the final volume has been removed. This results in a waste of 1625 g/ part steel and **260 kg/ton salable steel**

8.4.3 Remanufacturing scenarios (RMS) Phase 4

As detailed in chapter 5, the remachining phase is assumed to have a removal ratio Volume remachining over Volume machining equal to $\frac{1}{27}$. This drives to a machining time and therefore lubricant consumption 27 times less important.

8.4.3.1 Aluminum transfer case

Liquid waste and air emissions

The volume of lubrication needed in aluminum remanufacturing scenarios machining is determined Table 8.22.

Table 8-22aluminum transfer case remachining lubricant consumption

Aluminum transfer case remachining (L/ton salable aluminum)							
Lubricant volume	Hydrocarbure	Water	Sulphur	Chlorine	Emulsifier	Anti corrosion	Biocides
0.385	0.11	0.27	0	0	0.0033	0.0013	0.0004
665.03	570	28	65.9	0	0	0.81	0.32

Solid waste

Given the fact that $\frac{1}{27}$ of the machining volume is removed in the remachining processes, the resulting solid waste for aluminum parts is **3.3 kg/ton salable aluminum.**

8.4.3.2 Steel gears

Air emissions and liquid waste

The volume of lubrication needed in steel remanufacturing scenarios machining is determined Table 8.23.

Table 8-23 steel gear remachining lubricant consumption

Steel gear remachining process (L/ton salable steel)							
Lubricant Volume	Hydrocarbure	Water	Sulphur	Chlorine	Emulsifier	Anti corrosion	Biocides
1.03	0.98	0.043	0.007	0	0.00074	0.00026	0.00007
166.2	157.9	6.98	1.18	0	0.117	0.046	0.016

Solid waste

With the assumption that $\frac{1}{27}$ of the machining volume is removed in the remachining processes, the resulting solid waste for aluminum parts is **9.5 kg/ton salable aluminum.**

8.5 End-of-life strategies emissions and waste summary

Table 8.24 and 8.25 summarize all data that have been defined in Chapter 8. 0 value indicate an absence of emission or waste whereas a – indicates a value that has not been determined in the chapter because of lack of information.

Table 8-24 Aluminum emissions and waste summary

END OF LIFE STRATEGIES	PARAMETERS	PROCESS					SCENARIOS
	PROCESS	Metal refining	Melting	Casting	Cleaning	Transfer case machining	TOTAL
DS	Co2 eq. [g/ton]	1484	0	-	0	-	1484
	Solid waste [kg/ton]	3000	0	75	0	90	3165
	Water waste [L/ton]	10000	0	105	0	1830	11935
RCS	Co2 eq. [g/ton]	0	-	-	0	-	0
	Solid waste [kg/ton]	0	25	75	0	90	190
	Water waste [L/ton]	0	320	100	0	1830	2250
RMS	Co2 eq. [g/ton]	0	0	0	4950	-	4950
	Solid waste [kg/ton]	0	0	0	0	3.5	3.5
	Water waste [L/ton]	0	0	0	4148	68	4216

Table 8-25 Steel emissions and waste summary

STRATEGIES	PARAMETERS	STEEL PROCESSES					SCENARIOS
	PROCESS	Metal refinng	Melting	Casting	Cleaning	Steel gear machining	TOTAL
DS	Co2 eq. [g/ton]	0	0	-	0	-	0
	Solid waste [kg/ton]	615	0	75	0	260	950
	Water waste [L/ton]	15000	0	105	0	188	15293
RCS	Co2 eq. [g/ton]	0	0	-	0	-	0
	Solid waste [kg/ton]	0	110	75	0	260	445
	Water waste [L/ton]	0	4000	105	0	188	4293
RMS	Co2 eq. [g/ton]	0	0	0	2477	-	2477
	Solid waste [kg/ton]	0	0	0	0	9.5	9.5
	Water waste [L/ton]	0	0	0	320	7	327

CHAPTER 9
DISCUSSIONS AND CLOSURE

As it has been demonstrated, processes have different impacts on the environment. These impacts might result from energy consumption, liquid and solid waste or pollutant emissions. In this chapter, a classification of the processes and a discussion on end-of-life strategies will be performed. The evaluation of scenarios impact begins here with the energy consumption parameter.

9.1 Most energy consuming processes and scenarios

9.1.1 Energy consuming processes for an aluminum transfer case

The energy consumption evaluation and the resulting classification of the processes have been performed Chapter 5 (Figure 5.12). Electrolysis and aluminum production are the highest energy consuming phases. They are part of the material purification phase, proper to disposal scenarios (DS). Sorting follows these two phases but is much less energy consuming. Melting and casting processes follow with a slight decrease in the energy consumption and finally cleaning and machining phases close the classification with negligible consumption compared to the other processes. The total energy consumptions of the three scenarios are reminded in Table 9.1.

Table 9-1 Aluminum scenarios energy consumption

Scenarios	Energy consumption [kWh/ton]
DS	29464
RCS	4205
RMS	2597

The results determined in Table 9.1 give a significant advantage to the re use scenarios and especially to remanufacturing scenarios that consume twice less energy that recycling scenarios. However, another approach of the processes energy consumptions would improve these first observations. In fact, it is important to notice that the purification of the material is responsible of 98% of the disposal scenarios energy consumption. The following Table 9.2 helps to classify the scenarios in function of the number of energy consuming processes present in the scenarios instead of their magnitude. The processes are ranked from 1 to 6 from the least to the largest energy consuming. If a process is present in a scenario, the related weight is added in the scenario balance. The total or score indicates the number of environmentally hazardous processes present in a scenario.

Table 9-2 Scenarios ranking

Processes		Metal refining	Sorting	Melting	Casting	cleaning	Machining	**TOTAL**
Rank		6	5	4	3	2	1	
Scenarios	DS	6	0	0	3	0	1	**10**
	RCS	0	5	4	3	0	1	**13**
	RMS	0	5	0	0	2	1	**8**

In Table 9.2, recycling scenarios have a higher score than disposal scenarios. This shows that recycling strategies have more handicapping processes than disposal even if

their global energy consumption is not as high. The process that appears to limit the positive impact of recycling is the metal melting.

To summarize, in the aluminum application, the processes with a negative impact from an energy perspective are the metal refining and the metal melting. Disposal and recycling scenarios have a negative impact on the environment and recycling scenarios have the most critical processes from an energy point of view.

9.1.2 Energy consuming processes for a steel gear

The classification of the steel gear processes by their energy consumption also performed in Chapter 5, and summarized Figure 5.13, lead to the observation that that Iron making is the most energy consuming process. Associated with steel, sinter making, they constitute the metal purification phase. As in the aluminum application, this phase has the highest negative impact from an energy perspective. This is followed by the sorting process and the EAF melting process. The machining and cleaning processes close the ranks with negligible consumption compared to the other processes as it was the case in the aluminum application.

Table 9-3 Steel gears scenarios energy consumption

Scenarios	Energy consumption [kWh/ton]
DS	6245
RCS	3160
RMS	742

Table 9.3 gives the global energy consumption of each scenario. The disposal scenario is the most energy consuming phase. As previously, a second approach is performed here to refine the conclusions about processes impacts. In table 9.4, the scenarios are compared thanks to processes weighting.

Table 9-4 Steel energy consumption frequency ranking

Processes		Metal refining	Casting	Sorting	Melting	Machining	Cleaning	Total
Rank		6	5	4	3	2	1	
Steel scenarios	DS	6	5	0	0	2	0	13
	RCS	0	5	4	3	2	0	14
	RMS	0	0	4	0	2	1	7

The recycling scenario has the highest total. This means that recycling scenarios have the most important number of processes highly energy consuming. Melting appears here to be the most influencing process. As in the aluminum application, this particular phase is proper to recycling scenarios and should attract the attention as much as metal refining phases.

9.1.3 Energy consuming phases, global closure

In the aluminum as in the steel application, the metal refining and the metal melting appear to be the keys of the scenarios negative impact from an energy point of view. As it was demonstrated in the previous chapters, these two processes are very different in the aluminum and in the steel application, involving different machines, fuels and primary materials. However, they lead to the same conclusions concerning their high energy consumptions.

9.2 Processes and scenarios generating high solid waste

9.2.1 Solid waste generated by aluminum transfer case production

As demonstrated before solid waste is mostly generated by metal refining, machining and melting processes. The proportions have been determined Chapter 8 summary and are summarized in Table 9.5. In addition to have the most significant impact from an energy point of view, the metal refining and the melting processes are also two of the three processes generating the most waste.

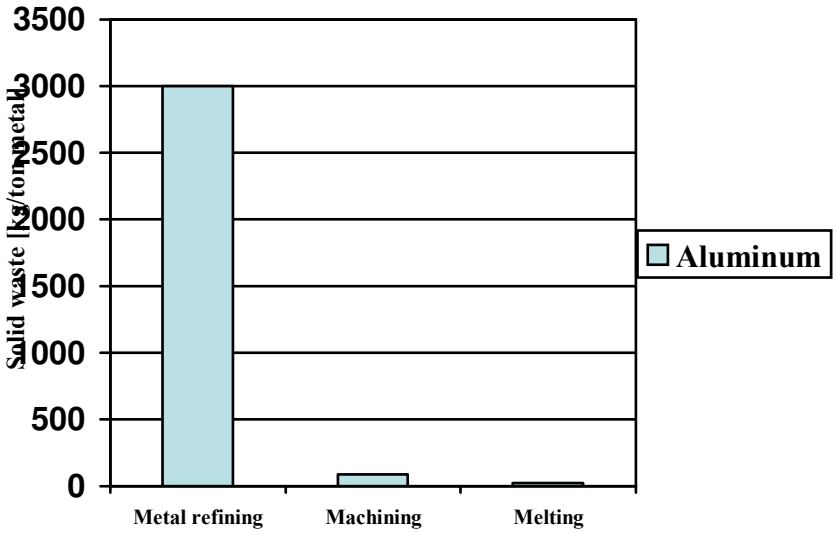


Figure 9-1 processes generating the most solid wastes

Table 9-5 Aluminum solid waste frequency ranking

Process		Metal refining	Machining	Melting	
Rank		6	5	4	Total
Scenarios	DS	6	5	0	11
	RCS	0	5	4	9
	RMS	0	5	0	5

9.2.2 Solid waste generated by steel gears production

Steel waste generation has been also determined chapter 8. Figure 9.2 illustrates the most waste generating processes.

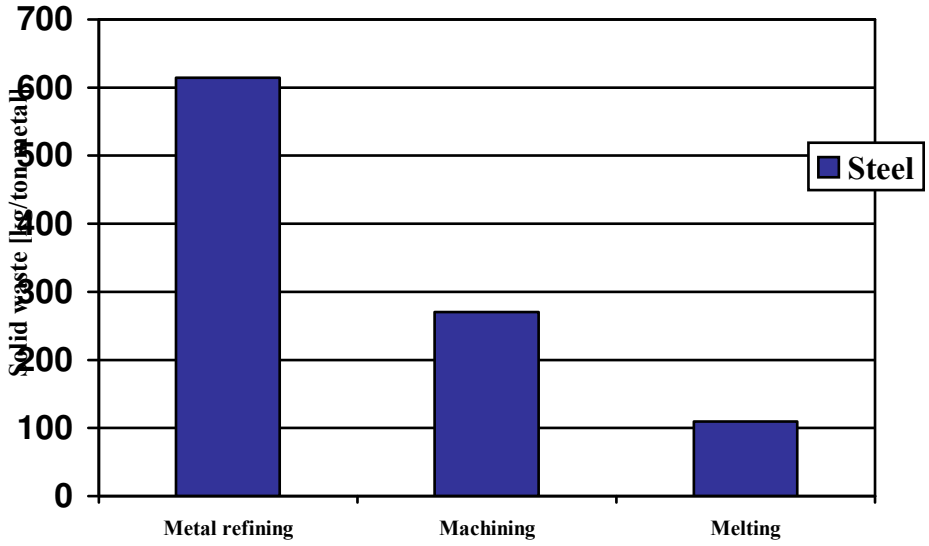


Figure 9-2 Steel processes generating the most solid waste

The processes generating the most solid waste are the same as in the aluminum application. In fact, metal refining, machining and finally melting are responsible of high amount of solid natural resource waste. It is important to notice the higher quantity of solid waste in melting and especially in machining processes. This is due to the bad moldability of steel compared to aluminum. In fact, in the case of steel, the functionality and the shape are entirely given to the part during the machining. Much more material has to be removed from the steel cast part than from aluminum cast.

Table 9-6 Steel solid waste frequency ranking

Process	Metal refining	Melting	Machining	Total
Rank	6	5	5	
DS	6	0	5	11
RCS	0	5	5	10
RMS	0	0	5	5

In the case of solid waste, Table 9.6 shows that Disposal scenarios have the highest scores and therefore, have more solid waste generating processes than the two other scenarios.

9.2.3 Processes resulting in high solid waste

Solid waste generated by processes has been evaluated in Chapter 8. Figure 9.3 summarizes and illustrates the results of aluminum and steel processes solid waste generation.

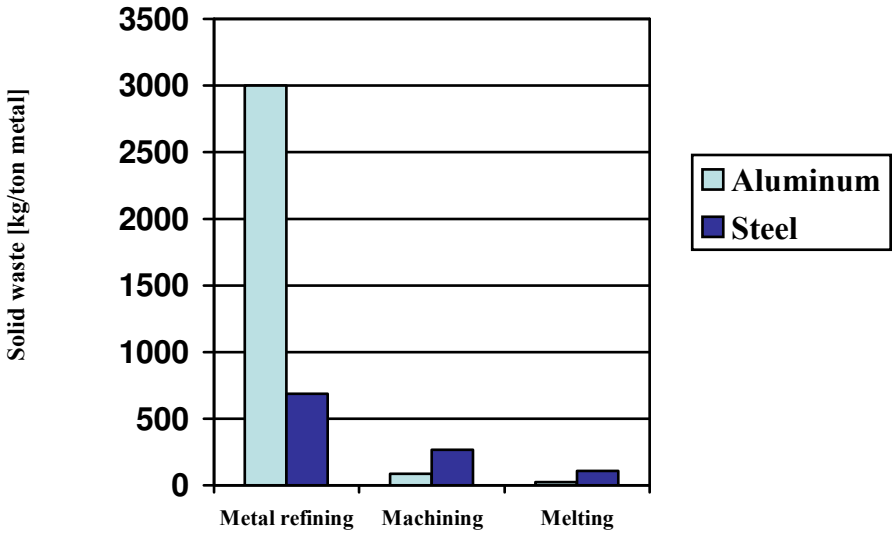


Figure 9-3 Steel and aluminum solid waste generating processes

In both examples, metal refining, melting and machining appear to generate the most waste. In both cases, metal refining has the highest amplitude. As it is shown in Table 9.5, while machining is common to the three scenarios and therefore, plays no role in their environmental impact differentiation, metal refining is proper to one scenario (DS) and melting is proper to one scenario as well (RCS). Therefore, from a solid waste point of view, disposal and recycling scenarios have a negative environmental impact.

9.3 Processes and scenarios generating high liquid waste

9.3.1 Liquid waste generated by aluminum processes

Liquid waste and more specifically water waste is a very important issue nowadays. Therefore, the water waste parameter should be considered as one of the most important parameters in the classification of processes environmental impacts. In fact, regulations have been enhanced make the companies clean their waste water before being able to reject it. These processes are expensive and are also responsible of energy consumption and pollutions. Figure 9.4 summarizes the results found in Chapter 8 concerning aluminum processes water wastes. Aluminum machining consumes the highest quantities of liquid (hydrocarbure and water). Liquid waste resulting from machining has been calculated in Chapter 8, Section 8.4.2. It included water and hydrocarbure consumption (lubricants composition calculations Table 8.18 and Table 8.21). In the inventory performed Figure 9.4, the two elements (water and oil) are distinctly reported in two different colors. Metal refining is the second one and finally aqueous cleaning follows. Whereas machining is common to the three scenarios, metal refining is only present in disposal scenarios and aqueous cleaning only appear in remanufacturing scenarios. These

two processes participate to the negative impact of aluminum end-of-life scenarios from a liquid waste point of view.

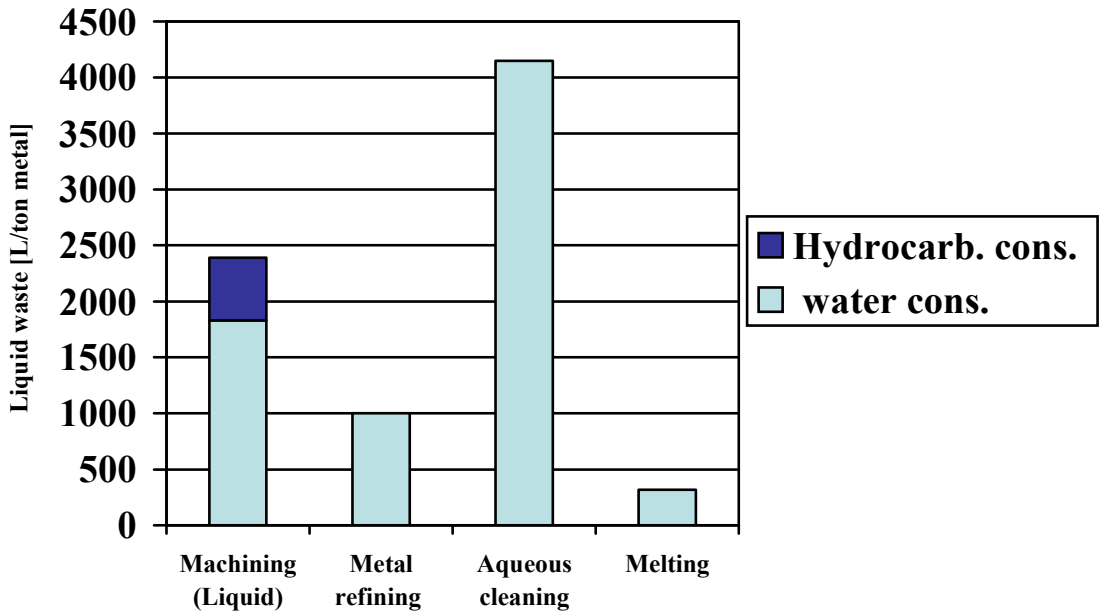


Figure 9-4 Liquid waste generated by aluminum processes

Table 9-7 Aluminum water waste frequency ranking

Process		Metal refining	Aqueous cleaning	Melting	Machining	
Rank		6	5	4	3	Total
Scenarios	DS	6	0	0	3	9
	RCS	0	0	4	3	7
	RMS	0	5	0	3	8

9.3.2 Liquid waste generated by steel processes

The liquid waste generated by steel processing is summarized in Figure 9.5. Metal refining appears to generate the highest amount of liquid waste, followed by machining and melting.

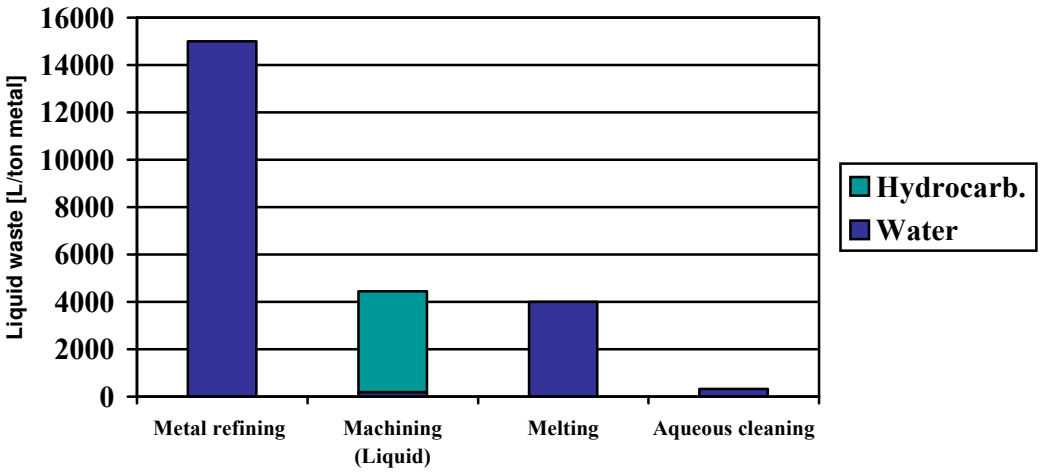


Figure 9-5 Liquid waste generated by steel production

Aqueous cleaning and machining generate also water waste but the quantities appear to be negligible compared to the other processes. For the same reasons as previously, metal refining and melting have the most significant environmental impact on scenarios from a liquid waste point of view.

Table 9-8 Steel processes water waste frequency ranking

Process		Metal refining	Melting	Aqueous cleaning	Machining	Total
Rank		6	5	4	3	
Scenarios	DS	6	0	0	3	9
	RCS	0	5	0	3	8
	RMS	0	0	4	3	7

9.3.3 Liquid waste generated by aluminum processes

As it is shown Figure 9.6, where aluminum and steel processes liquid wastes are summarized, the liquid waste produced by processes and the orders are different between the two case studies. In fact, whereas metal melting is the first liquid waste producer in steel scenarios, machining is the first in aluminum scenarios. This is why, as metal refining appears to be a high liquid waste producer for both material productions, aqueous cleaning appears to be a problem only in aluminum scenarios. As it was demonstrated in Chapter 5 and Chapter 8, this difference is due to the geometry of the parts more than to their material.

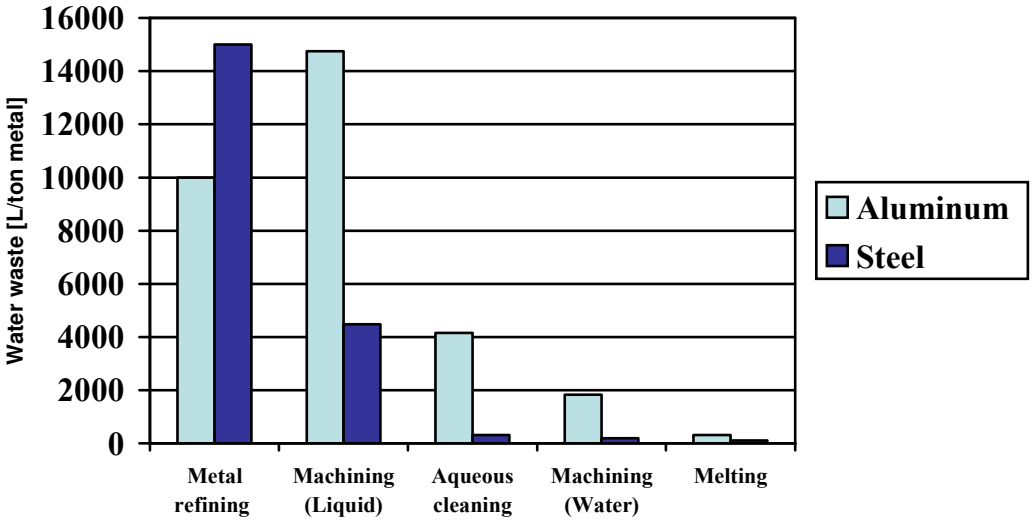


Figure 9-6 Aluminum and steel processes liquid waste

In both applications, disposal scenarios have a negative impact on the environment. In aluminum applications, remanufacturing strategies have a strong disadvantage while in

steel production recycling scenarios have a negative impact. The liquid waste parameter depends on the material (metal refining and melting) but also on the geometry of the part. The higher the volume of the part is and the higher dirty surface is, the more water is going to be consumed.

9.4 Processes emitting the highest quantities of pollutants

9.4.1 Aluminum processes pollutants generations

The pollutants emissions have been studied in Chapter 8 and summarized in Figure 9.7. The results displayed do not take in consideration the emissions produced by energy generation. The only pollutions described here are greenhouse gas emissions. In aluminum scenarios, the two main processes that appear to emit the most pollutants are cleaning and metal melting.

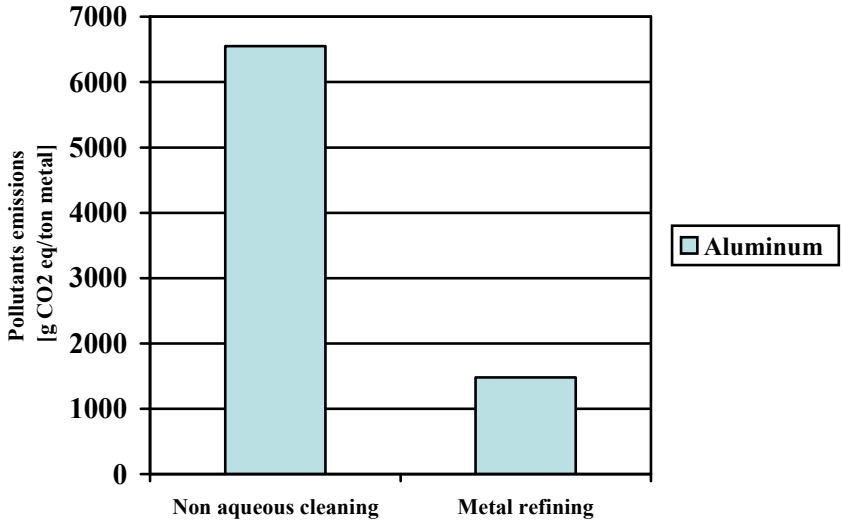


Figure 9-7 Aluminum processes pollutants emissions

Cleaning processes is only present in remanufacturing scenarios and metal refining is only present in disposal scenarios. Therefore, from a pollutants emissions point of view, remanufacturing and disposal scenarios have a negative environmental impact.

9.4.2 Steel processes pollutants generations

The important greenhouse gases emitted by steel processes are determined Figure 9.8.

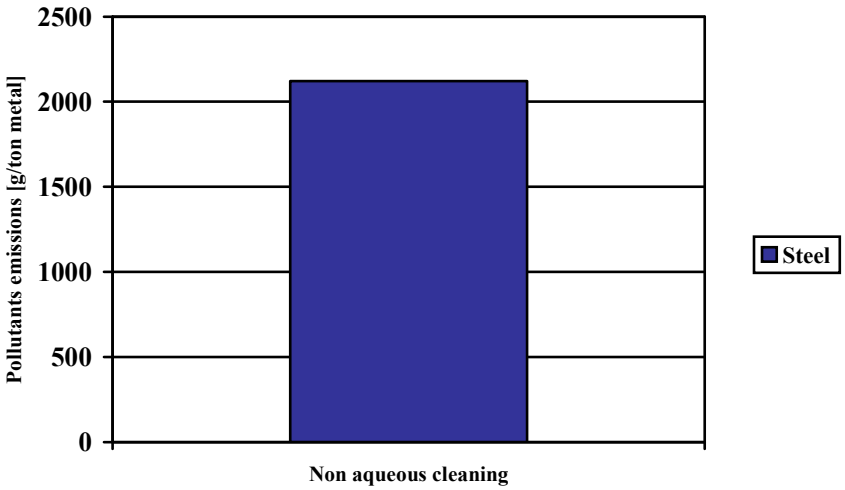


Figure 9-8 Steel processes pollutants emissions

As it appears in figure 9.8, cleaning processes are the most noticeable greenhouse gases generators. Consequently, steel remanufacturing scenarios have a negative impact from a greenhouse gas emissions point of view.

9.4.3 Steel and aluminum processes pollutants generations summary

Aluminum and steel pollutants are summarized and compared in Figure 9.9.

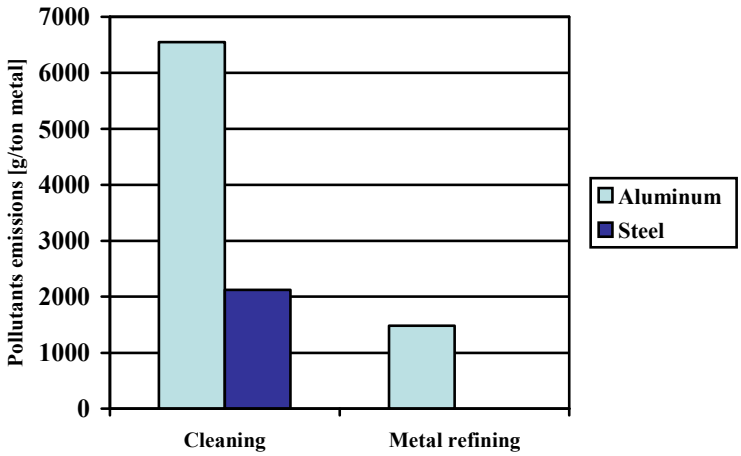


Figure 9-9Steel and aluminum processes pollutants emission

The previous Figure shows that aluminum production results in much more emissions than steel production. Therefore, remanufacturing scenarios have a negative environmental impact from a greenhouse gas emission point of view and aluminum remanufacturing is more critical than steel remanufacturing.

9.5 Conclusion on processes environmental impact

The global observations about scenarios environmental impacts are summarized in Table 9.10. In the two last columns, the three end-of-life strategies appear in the order of the coefficient of hazardous processes frequency that was calculated in the previous sections (Table 8.2, Table 8.4, Tablen8.5, Table 8.6, Table 8.7, Table 8.7). It is important to notice given in the two last columns do not always corresponds to the ranking depending on energy consumption, waste and emissions magnitudes. Table 9.9 will help to draw the conclusions of this thesis. It is therefore a very important reference

Table 9-9 scenarios global environmental impact

	Rank	Aluminum processes highest magnitude	Steel processes highest magnitude	Aluminum scenarios total value	Steel scenarios total value	Aluminum environmentally hazardous processes frequency	Steel environmentally hazardous processes frequency
Energy consumption [amplitude kWh/ton]	1	Metal refining	Metal refining	DS = 29464	DS= 6245	RCS	RCS
	2	Melting	Casting	RCS = 4405	RCS =3160	DS	DS
	3	Sorting	Sorting	RMS = 2597	RMS = 742	RMS	RMS
Solid waste [amplitude kg/ton]	1	Metal refining	Metal refining	DS =3165	DS= 615	DS	DS
	2	Melting	Melting	RCS = 190	RCS = 445	RCS	RCS
	3	Machining	Machining	RMS = 3.5	RMS = 9.5	RMS	RMS
Water waste [amplitude L/ton]	1	Metal refining	Metal refining	DS = 11935	DS = 15293	DS	DS
	2	Aqueous cleaning	Melting	RMS = 4216	RCS = 4293	RMS	RCS
	3	Machining	Aqueous cleaning	RCS = 2250	RMS = 327	RCS	RMS
	4	Melting	Machining				
Polltants emissions [amplitude g CO2 eq/ton]	1	Non aqueous cleaning	Non aqueous cleaning	RMS = 4950	RMS = 2477	RMS	RMS
	2	Metal refining		DS = 1484	RCS = DS = 0	DS	RCS/DS
				RCS = 0		RCS	

In this table, metal refining appears to have the highest frequency in most of the classifications. In fact, aluminum refining consumes 29000 kWh/ton aluminum which is 98 of the total energy consumption of disposal scenarios. Steel refining has a lower magnitude. It consumes 4485 kWh/ton salable steel. Nevertheless, this is also 70 % of the total steel disposal energy consumption. Solid waste generated by this phase is also the highest compared to all other scenarios. In fact with, in aluminum scenarios, this process is responsible of 3 tons waste/ton aluminum. In steel scenarios, the rate of 615 kg/ton steel is lower but is still important. To conclude, water consumed during this phase has also the highest amplitude compared to all processes. With 10000 L/ ton aluminum water wasted and 15000 L/ton steel water wasted, the refining process including ore extraction, mechanical and chemical refineries should be considered as the most critical process in any end-of-life strategy. Given the fact that this material refining only exists in disposal

strategies, it proves their highest negative impact on the environment from an energy consumption, solid waste and liquid waste point of view.

The second environmentally harmful process is the metal melting. This process appears to have an influence on three of the four parameters tested (energy consumption, solid waste and water waste). Nevertheless, melting is more critical from and energy point of view in aluminum scenarios with 1200 kWh/ton aluminum compared to 700 kWh/ton steel and more critical from a waste point of view in steel scenarios with a minimum of 110kg/ton steel compared to 25 kg/ton aluminum. These melting characteristics participate to the negative environmental impact of recycling scenarios. Eventually, cleaning is the third critical process that wastes high amounts of water in the case of aqueous washing and high amounts of greenhouse gases in the case of non-aqueous cleaning. In fact, in the case of solvent use instead of water use, 6552 g $CO_{2\ eq}$/ton aluminum and 2121 g $CO_{2\ eq}$ /ton steel are rejected into the atmosphere. This cleaning phase is only present in remanufacturing scenarios. Therefore, remanufacturing strategies have also a negative impact from a greenhouse gas emissions point of view.

These conclusions about scenarios impacts are given for general applications, where little information about manufactured parts is known. In fact, more accurate conclusions might be possible. A case by case study can be performed as well to find which of the processes influence the most the scenarios.

To conclude, this thesis proves the positive environmental impact of remanufacturing strategies from and energy and a solid waste point of view. Liquid waste and pollutants emissions due to the phases of cleaning are the problematic processes of remanufacturing strategies. However, these weaknesses can be solved by the development of non-

pollutant and organic solvents. Some of these technologies are already on the market and should develop thanks to the help of strong governmental regulations and thanks to the reasonable retail prices.

However, governmental regulations, low prices and evolutions of the cleaning processes will be useful as long as the supply chain is correctly managed. In fact, in the case of a bad organization of the material collection and more generally of the material transportation, all efforts realized on the production chain might be annihilated.

9.6 Conclusions on transportation impact on end-of-life strategies savings

As it has been demonstrates, re use strategies might have an overall positive impact on the environment, especially from a solid waste and an energy point of view. However, as it was demonstrated in Chapter 6, inappropriate management of the supply chain can lead to a complete annihilation of the positive results determined in the previous section. The main parameters that have a direct impact on the relative energies of scenarios are the distance, the type of transportation and the amount of usable or reusable material in the containers transported. In order to guaranty low energy consumption to reuse strategies, long distances covered by transportation have to be performed by low energy consumption rates vehicles. The lowest energy consumption rates studied here are ships (0.045 kWh/ton –km), followed by trains (0.06 kWh/ton –km) and finally trucks (0.18 kWh/ton –km). The other parameter of usable or reusable mass rate in the container is also very important. In fact, large amount of usable material have to be privileged. While is more likely to be a constant in disposal scenarios, it can be chosen in reuse scenarios. The recommended high amount of usable material can be reached by a preliminary material sorting. This presorting is currently performed municipal recycling companies

who ask their customers (city inhabitants) to sort their waste before collection. This model should be spread to industrial waste. However, a study of cost should be realized before drawing any categorical conclusion. In fact, the presorting of municipal waste is a free, non energy consuming process. Therefore, it is not enough to prove the entire viability of the organization from and industrial point of view.

To conclude, thanks to the study of two different cases, it has also been proven that the closer the energy consumptions between scenarios are, the higher effect the transportation parameters have on the energy consumptions. In fact, the closer the energies are between scenarios, the shorter the distances should be and the higher the usable or reusable material container content should be.

9.7 Future work

As it was introduced in this thesis, design for reuse was out of the study boundaries. However, research in this domain could lead to the definition of remanufacturability parameters. These criteria could results in a more accurate remanufacturing sorting analysis. In fact, remanufacturing sorting was assimilated to recycling sorting. This is a very approximate assumption that should be improved in a future work.

Another side of the sorting process that has not been studied here is the uncertainty in the origin of the part. In fact, the life condition of the part is an important criterion that determines the viability of the remanufacturing process. The user, the function and the age of the part are important characteristics that can influence the durability of the remanufactured part. This should also be the focus of a future research.

The interconnectivity between scenarios was not considered here. This has a very important consequence in the transportation conclusions. In the case of reuse strategies,

the collections of aluminum and steel have been studied independently. Nevertheless, in the industry, aluminum and steel can be collected together. This would lead in a significant decrease of transportation energy consumption and of the related air emissions.

As mentioned in this thesis, remanufacturing processes are being developed. Adding material on used surfaces is an important process that needs to be explored deeper and should be taken in consideration in the remanufacturing impact analysis. The addition of material on used surfaces might increase the reusability capacity of the parts. For certain techniques, prices remain high and systems need to be improved. Nevertheless, the progresses performed in this evolving domain should be followed to update the analysis of this thesis. The same observation is possible with cleaning and lubricating systems where new technologies (Ex: CO_2 blasting for cleaning processes and Minimum Quantity of Lubricant (MQL) for machining lubricants) might help to reduce the negative impact of remanufacturing strategies determined in this Thesis.

To conclude, air pollutants and their consequences need to be deeper evaluated. The polluting processes have been underlined in this thesis. Research in the interaction between emissions such as criteria pollutants and greenhouse gases could lead to a better comparison between scenarios from a more global perspective.

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